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Wireless Sensor Technology Selection for I4.0 Manufacturing Systems

By

Badr Mohamed Mahmoud Abdelrehim

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Wireless Sensor Technology Selection for I4.0 Manufacturing Systems

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26 February 2020

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ABSTRACT

The term smart manufacturing has surfaced as an industrial revolution in Germany known as Industry 4.0 (I4.0); this revolution aims to help the manufacturers adapt to turbulent market trends. Its main scope is implementing machine communication, both vertically and horizontally across the manufacturing hierarchy through Internet of things (IoT), technologies and servitization concepts. The main objective of this research is to help manufacturers manage the high levels of variety and the extreme turbulence of market trends through developing a selection tool that utilizes Analytic Hierarchy Process (AHP) techniques to recommend a suitable industrial wireless sensor network (IWSN) technology that fits their manufacturing requirements.

In this thesis, IWSN technologies and their properties were identified, analyzed and compared to identify their potential suitability for different industrial manufacturing system application areas. The study included the identification and analysis of different industrial system types, their application areas, scenarios and respective communication requirements. The developed tool's sensitivity is also tested to recommend different IWSN technology options with changing influential factors. Also, a prioritizing protocol is introduced in the case where more than one IWSN technology options are recommended by the AHP tool.

A real industrial case study with the collaboration of SPM Automation Inc. is presented, where the industrial systems' class, communication traffic types, and communication requirements were analyzed to recommend a suitable IWSN technology that fits their requirements and assists their shift towards I4.0 through utilizing AHP techniques. The results of this research will serve as a step forward, in the transformation process of manufacturing towards a more digitalized and better connected cyber-physical systems; thus, enhancing manufacturing attributes such as flexibility, reconfigurability, scalability and easing the shift towards implementing I4.0.

DEDICATION

To my parents and my sister, for their continuous support
To my supervisor, for her continuous help and guidance

ACKNOWLEDGMENTS

I would love to express my great appreciation to my supervisor Professor Hoda ElMaraghy for her continuous guidance and support during this journey. This thesis would not have been at this knowledge and quality levels without her sincere effort and time. Her support was not only limited to supervising and recommending research topics; she always encourages her graduate students to never give up, think critically and outside the box. One of the most challenging experiences during this journey was selecting a research topic, but with the help of Professor Hoda ElMaraghy, we overcame this obstacle and succeeded.

I would like to also thank all my committee members for their valuable feedback. Great thanks goes to Professor Waguih ElMaraghy for his valuable comments, recommendations, and feedback during the Intelligent Manufacturing Systems Centre (IMSC) meetings and the committee meetings.

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CHAPTER 1

INTRODUCTION

1.1 Research Motivation

Today, the significant increase in customer demands and needs of personalization and customization is remarkable. For the last few years, this increase has been the industry's biggest challenge to constantly cope with it and achieve a quick responsive strategy that is efficient and cost effective (ElMaraghy and ElMaraghy 2016). Since this increase is inevitable, it is evident that the industry is constantly shifting towards higher variability, personalization and customization of products using leaner, smarter and flexible production strategies (ElMaraghy 2019). Hence, it has led the manufacturers to shift from mass production to mass customization, and acquire the characteristics of flexibility, reconfiguration, and most recently smartness (ElMaraghy 2019) .

The term smart manufacturing has surfaced as an industrial revolution due to the technological advancements that emerged; this revolution aims to help the manufacturers adapt to turbulent market trends. The concept of smart manufacturing appears in Germany as the 4th Industrial revolution (I4.0). Its main scope is implementing machine communication, both vertically and horizontally across the manufacturing hierarchy through Internet of things (IoT), technologies and servitization concepts (Thoben, Wiesner, and Wuest 2017). Furthermore, It builds on the visions and enablers of previous manufacturing paradigms, spanning from low cost and dedicated machines to high variety and flexible machines, however, promising new levels of responsiveness, flexibility and productivity (Andersen et al. 2017; Koren and Shpitalni 2010).

Resulting smart factories contain cyber-physical systems (CPS) such as machines, vehicles and workpieces that are equipped with technologies such as RFIDs, sensors, microprocessors, etc. These technologies are characterized by being able to collect, analyze and evaluate data themselves, connect and communicate with other systems, and initiate actions (Thoben, Wiesner, and Wuest 2017); thus, fulfilling the dynamic customer demands.

According to the aforementioned, connectivity plays a significant role as it is the key enabler to implement Industry 4.0 by providing the ability to exchange data amongst participants within a functional domain, across functional domains within a system and across systems (Joshi et al. 2017). However, since connectivity within cyber physical systems is proprietary to specific manufacturers, the current/emerging trend of research in this area has shifted towards communication technologies within sensor networks.

Research in communication technologies that are established in Industrial environments can be broadly divided into two categories, wired and wireless. The wired communication networks in the industries were designed to target four specific objectives including real-time assurance, guaranteed functional safety, security, and centralized supervisory control of decentralized processes. However, although the wired networks offered modest data rates and reliability, it failed in offering scalability, cost efficiency, and efficient network deployment which led the researchers to look into wireless communication solutions in Industrial environments and specifically Industrial Wireless Sensor Networks (IWSNs).

IWSNs have emerged as an efficient and cost-effective solution for industrial automation and process control. In addition, they have many advantages associated to them such as their low installation costs, scalability, flexibility, self-organization, localized processing, interoperability and ease of deployment. However, they were lacking reliability in achieving real time constraints required by critical application areas within the manufacturing industries.

Due to the recent advancements and developments in the previous and current wireless technologies, solutions to issues related to reliability, security, etc. have been tackled and overcome by many researchers through different methodologies, which in turn shifted the manufacturers to re-consider choosing wireless technologies to automate, monitor, and control different industrial systems.

These significant research developments have given new heights to this market resulting in momentous rise in its projected value ranging from $944.92 million to 3.795 Billion in coming years (Raza et al. 2017). Thus, to cope with the projected market trends, and satisfy the demands of sophisticated industrial applications and to meet the crucial deadlines in highly sensitive industrial atmosphere, a study of the current wireless technologies and their relative advancements that are able to enhance the overall performance of manufacturing systems providing them with flexibility, scalability, adaptability, self-configuration, and self-healing characteristics is much needed.

1.2 Statement of Engineering Problem

Performing an accurate selection of wireless technology that matches the industrial manufacturing system requirements it is intended to be implemented to, in order to avoid harming the overall performance of the manufacturing system remains a challenge for small and medium manufacturers.

1.3 Objectives

This research aims to investigate the different types of industrial manufacturing systems, identify the different application areas associated to them, and identify the different scenarios associated to the identified application areas. It also aims to identify the requirements relative to each use scenario in regard to their communication traffic (data packets sent over the network), reliability, data rates, latency, cycle times, range, etc. and investigate the essential requirements that can take a toll on the manufacturing system's overall performance if not met. It also aims to investigate the available different wireless technologies to be implemented in an industrial environment and identify the relative properties needed to determine their industrial suitability in different scenarios. Finally, it aims to create a selection-road map that uses the identified scenarios and the identified wireless technologies to determine a suitable wireless technology selection in a step-by-step methodology. The developed selection process is then validated through a real industrial case study.

1.4 Research Thesis Hypothesis

The research thesis statement of this research could be formulated as follows:

A suitable wireless technology recommendation for different industrial manufacturing systems that could provide an enhanced communication performance, flexibility and scalability aiding their transition/shift towards I4.0 could be achieved through considering the different industrial systems' classes, communication traffic types, communication requirements and utilizing AHP decision support techniques.

1.5 Scope of Research

The scope of this research and the boundaries of this work are as follow:

1. The communication technology studied is limited to Industrial Wireless Sensor Networks.
2. The Industrial Wireless Sensor Network technologies considered are limited to five - namely, Bluetooth, Wi-Fi, ZigBee, WirelessHART, and ISA100.11a.
3. The Industries to which research is applied are limited to industrial automation industries such as factory automation industries and process automation industries.

1.6 Thesis Structure

This thesis is presented in 5 chapters, including this introduction chapter. Chapter 2 summarizes the available literature review on several topics related to this work. In particular, it includes a summary of Wireless Communication technologies, Industrial Wireless Sensor Networks, The OSI stack architecture and its different layers, network topologies, and research contributions to this topic. Research gaps identified in the literature review are also presented in this chapter.

Chapter 3 describes the AHP decision support technique approach and methodology and the tools used for formulating the problem using the IDEF0 modeling technique. Chapter 4 shows the results and discussion of the presented industrial case study scenarios. Chapter 5 provides a conclusion, a discussion of the novelty of the presented research, and suggestions for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter of the thesis, a large amount of previous work addressing industrial wireless communication technologies and different evaluation and comparison approaches, OSI stack architecture and its different layers, network topologies, industrial manufacturing system classes and their relative communication traffic types are reviewed. The first section of the literature survey is concerned with the topic of wireless communication technologies and industrial wireless sensor actuator network technologies. It includes a detailed review of wireless communication technologies in general and in specific the types of industrial wireless sensor network technologies available namely, Wi-Fi, Bluetooth, ZigBee, WirelessHART, and ISA100.11a. The second section of the literature survey is about the different classes of industrial manufacturing systems and describes the different application areas and communication traffic types associated with them. The third and last section of this chapter is about recent and previous work contributed towards evaluating, comparing and determining suitability of different industrial wireless technologies in different industrial environments.

2.2 Wireless Communication technologies

The objective of Industry 4.0 is to connect and integrate traditional industries, particularly manufacturing, to realize flexibility, adaptability, and efficiency and increase effective communication between producers and consumers (Gorecky et al. 2014; Wan, Cai, and Zhou 2015). Industry 4.0 refers to cooperation between different factories that are generally based in different remote places. Therefore, communications and networks play an important role in

Industry 4.0 (Li et al. 2017). The communication networks established in industrial environments can be broadly divided into two categories, wired and wireless. The wired communication networks were designed to target four specific objectives including real-time assurance, guaranteed functional safety, security, and centralized supervisory control for decentralized processes. However, although, the wired networks offered modest data rates and reliability, it failed in offering scalability, cost efficiency, and efficient network deployment which are attributes that current manufacturers are interested in implementing. Thus, leading the researchers to look into wireless communication solutions for industrial automation (Al Nuaimi, Sallabi, and Shuaib 2011).

Wireless networks play a key role in enabling the flexibility and scalability of Industrial Internet of Things (IIoT) systems, through its ability to support low power and long-range communication for devices. Furthermore, wireless technologies are considered key enablers of the deployment of Industry 4.0 framework and can be used for smart factories and intelligent manufacturing systems through the deployment of wireless sensor networks (WSNs) and in specific, industrial wireless sensor networks (IWNs) (Li et al. 2017).

2.2.1 Industrial Wireless Sensor Networks (IWSN)

A wireless sensor network can be defined as a network of devices, denoted as nodes. Their basic functionality is to corporately sense, gather, process, and publish data in the surrounding environment. Sensor nodes could be designed in the form of small devices with low power consumption, limited memory for calculating and communication. They are required to have capabilities of routing, dynamically searching, positioning, and self-recovery in order to enable flexible topology of the network against harsh and unpredictable environment (Wang 2011). Fig.2.1 shows the architecture of wireless sensor network. The data is forwarded, possibly via multiple hops, to either a controller or monitor sink that can be used locally or is connected to other networks through a gateway. The nodes can be stationery or moving, location aware or not, and homogenous or not (Shahzad and Oelmann 2014).

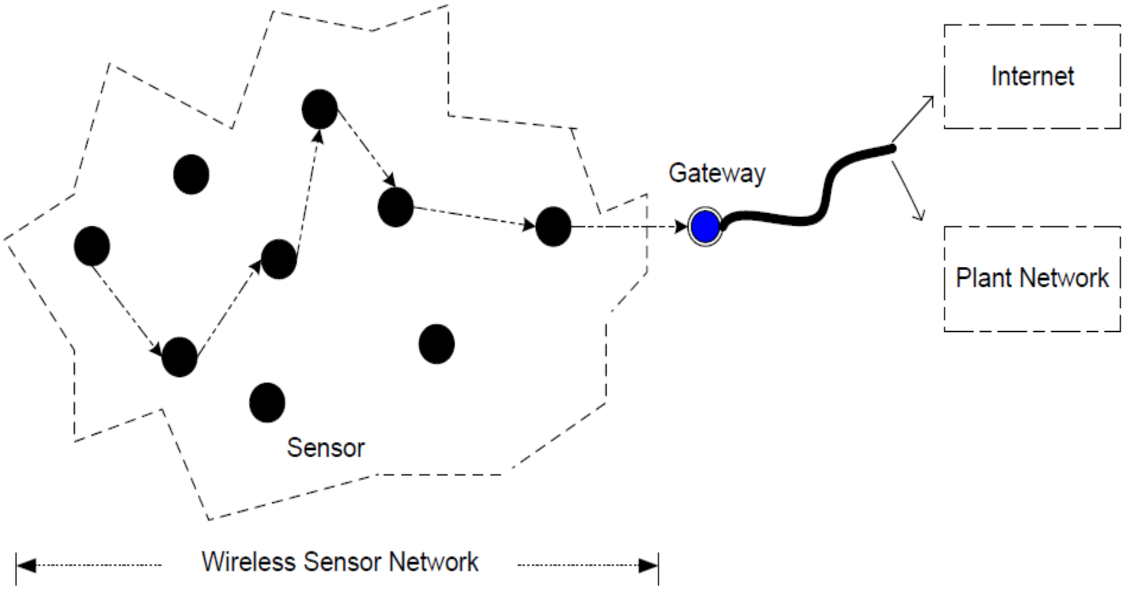


Figure 2.1 - Architecture of wireless sensor networks (Wang 2011)

Moreover, WSNs are gradually adopted in the industrial world due to their advantages over the wired networks. In addition to saving cabling costs, WSNs widen the realm of environments feasible for monitoring. Thus, adding actuating and sensing capabilities to objects in the physical world and allowing for communication among them (Christin, Mogre, and Hollick 2010).

To further illustrate the framework of IWNs, a plant or factory interior perspective is used as shown in Figure 2.2 below. Thus, the communications system can be divided into four components: smart-entities, inter-IWNs, beyond IWNs, displayers, and servers. Within IWNs, smart entities such as workmen, AGVs, machines, and ordinary sensors with wireless transceivers could be regarded as wireless nodes that are connected to form an IWN by wireless radios. Furthermore, beyond IWNs, the access point nodes and the gateway create a bridge to other networks such as cellular, and wired, etc. Higher level data applications including data servers, management, controllers, and displayers may be based on these specific networks (Li et al. 2017).

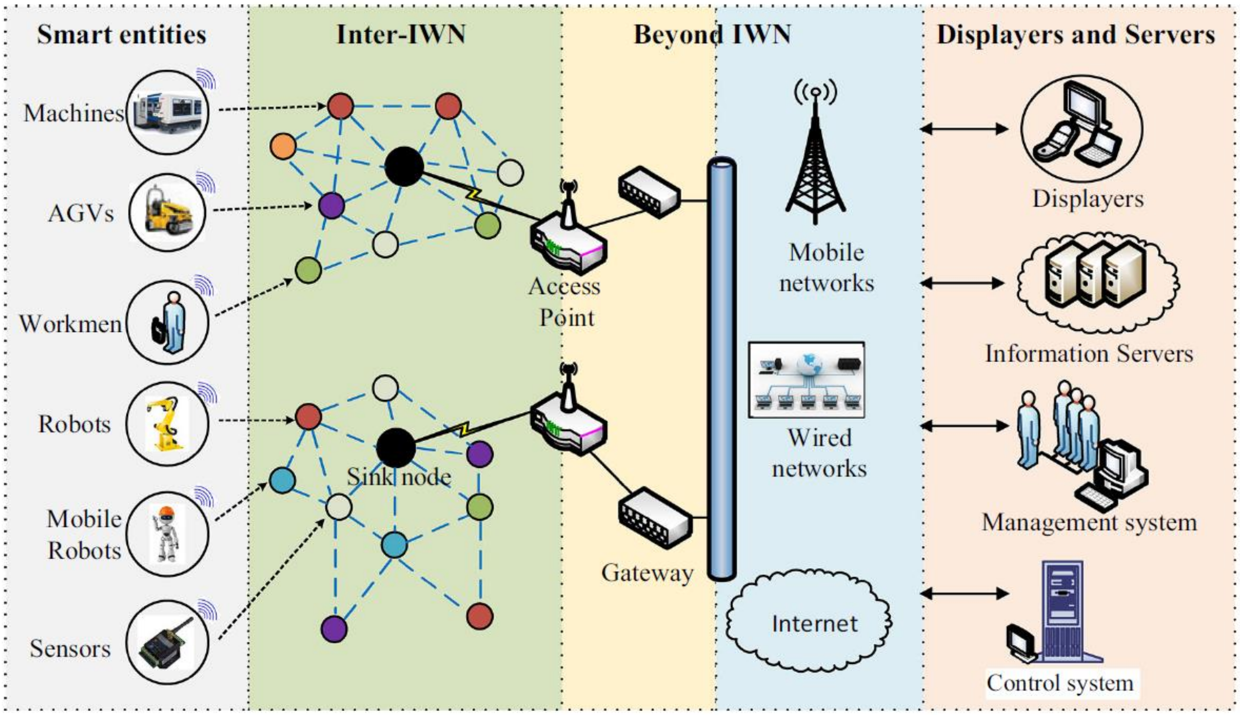


Figure 2.2 - Industrial wireless network schematic diagram ((Burg, Chattopadhyay, and Lam 2018)

2.2.2 Industrial Wireless Sensor Network Architecture

Furthermore, before introducing the different industrial wireless technologies available that can cope with the stringent industrial system types requirements, an understanding of the Industrial wireless sensor networks (IWSNs) architecture is needed. The performance of IWSNs is mainly influenced by multiple components namely, hardware, topology, channel access schemes, network architecture, data collection, interconnectivity, and security schemes. Furthermore, IWSNs scheme selection, regardless of its critical or non-critical application use have some benefits and limitations. Therefore, it is very important to have a careful selection of certain attributes (Raza et al. 2017).

Some of the key influencing factors are discussed below:

1) **Network Topology:** It greatly influences the target application areas. In addition, any industrial wireless sensor network architecture has different network topologies, each having different characteristics. In general, the nodes within a network are usually formed in a star, mesh, and tree topologies (Sharma, Verma, and Sharma 2013; Raza et al. 2017; Zhao 2011).

a) Mesh Topology: In this topology, each node is connected to multiple nodes allows the networks to offer improved reliability within larger networks and enhanced self-healing characteristics. However, this results in extended delays as a consequence of multiple links to gateway allowance and also affects the flexibility to opt most stable route for information communication.

b) Tree topology: offers dedicated links that allows less information overhead. In addition, a fixed number of hops is determined for nodes communication which in turn provides deterministic behavior to the communication (Raza et al. 2017). Also, it offers gradient information field that limits the information packets straying from the path. Furthermore, added delay is a possible result in time sensitive industrial applications if extended branches were used.

c) Star topology: Enhanced real-time data delivery is an advantage in this topology, this is due to its offering of direct access to the gateway. However, an increased number of connected nodes results in a reduced reliability especially in contention based channel access schemes (Raza et al. 2017).

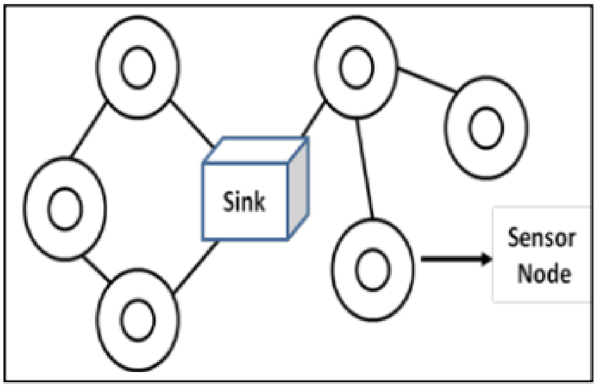


Figure 2.3 - mesh topology (Sharma, Verma, and Sharma 2013)

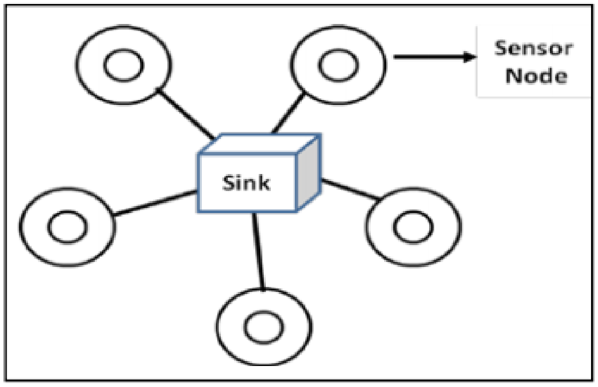


Figure 2.4 - star topology (Sharma, Verma, and Sharma 2013)

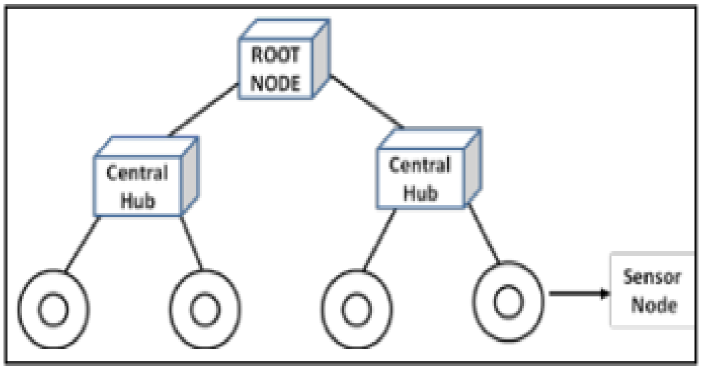


Figure 2.5 - Tree topology (Sharma, Verma, and Sharma 2013)

2) Channel Access Schemes: There are several channel access schemes offered within industrial wireless sensor networks, however, according to (Raza et al. 2017), only two were mentioned, namely, Timed-division medium access scheme (TDMA), and CSMA/Collision Avoidance (CSMA/CA). They are both derived from the IEEE 802.15.4 and IEEE 802.15.4e standards and they are commonly used to access channel schemes.

a) TDMA: In TDMA based channel access, a time slotted access for data communication is followed. Here synchronization beacons synchronize the nodes and schedules for each node a pre-specified time slot. This results in a guaranteed channel access and is suitable for use in regulatory and open loop control where periodic communications are required.

b) CSMA/CA: In CSMA/CA based channel access, the nodes use opportunistic communication that depends on the channel availability to access the channel. However, with no dedicated bandwidth specified, a node cannot have a guaranteed access to the channel. This makes this scheme not safe to use for critical application areas. Moreover, a reliability issue also arises using this access scheme with the increase of the number of the connected nodes.

c) Hybrid: Because the two schemes have different application areas to be used at and because industrial systems might have both areas together, a hybrid channel access scheme of both the TDMA and CSMA/CA were introduced. This allows the use of both the TDMA, and the CSMA/CA adaptively, to improve the overall performance of the network (Yang et al. 2015; El-Hoiydi 2002).

2.2.3 Wireless Sensor Networks Open System Interconnection (OSI) layers

Wireless sensor networks follow a communication architecture very similar to the OSI model. The OSI model was created within the International Standards Organization (ISO). Moreover, the model defines seven layers that describe how applications running upon network-aware devices may communicate with each other (Briscoe 2000). The model is generic and applies to all network and media types. However, in a wireless sensor network, only five layers are needed, namely, application layer, transport layer, network layer, data link layer and physical layer as shown in Figure 2.6. A discussion of the most relevant features of each communication layer was presented by (Koubâa, Alves, and Tovar 2005; Briscoe 2000; Akyildiz et al. 2002).

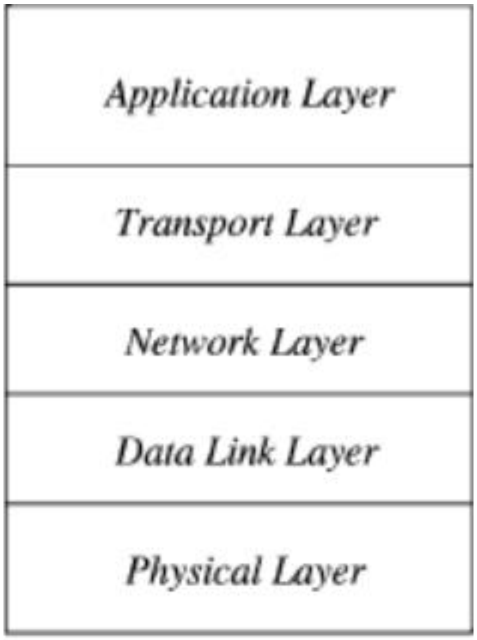


Figure 2.6 - WSN Protocol stack
(Wang and Balasingham 2010)

The following are the definitions they provided of each communication layer:

a) Physical Layer: It is responsible for frequency selection, carrier frequency generation, detecting signals, and providing the appropriate signal modulation taking into consideration the allowed frequency ranges for the specified application. Also, it has to dedicate a special care to the inherent constraints, including low-power consumption and hardware design.

b) Data Link Layer: The data link layer is divided into two sublayers, the Logical Link Control (LLC) and Medium Access Control (MAC). The Medium Access Control sub-layer is only considered due to its significant effects in terms of energy-consumption and real-time issues. The Data Link's layer common functionality is to schedule the available data for transmission in the overall network, providing each node with the mechanism to make a decision of when and how to access the shared medium between the other nodes to transmit its data. This functionality is the responsibility of its MAC sublayer protocols. Moreover, existing MAC protocols in wireless sensor networks are divided into three categories shown in Figure 2.7; they are, scheduling based, collision free, and contention based.

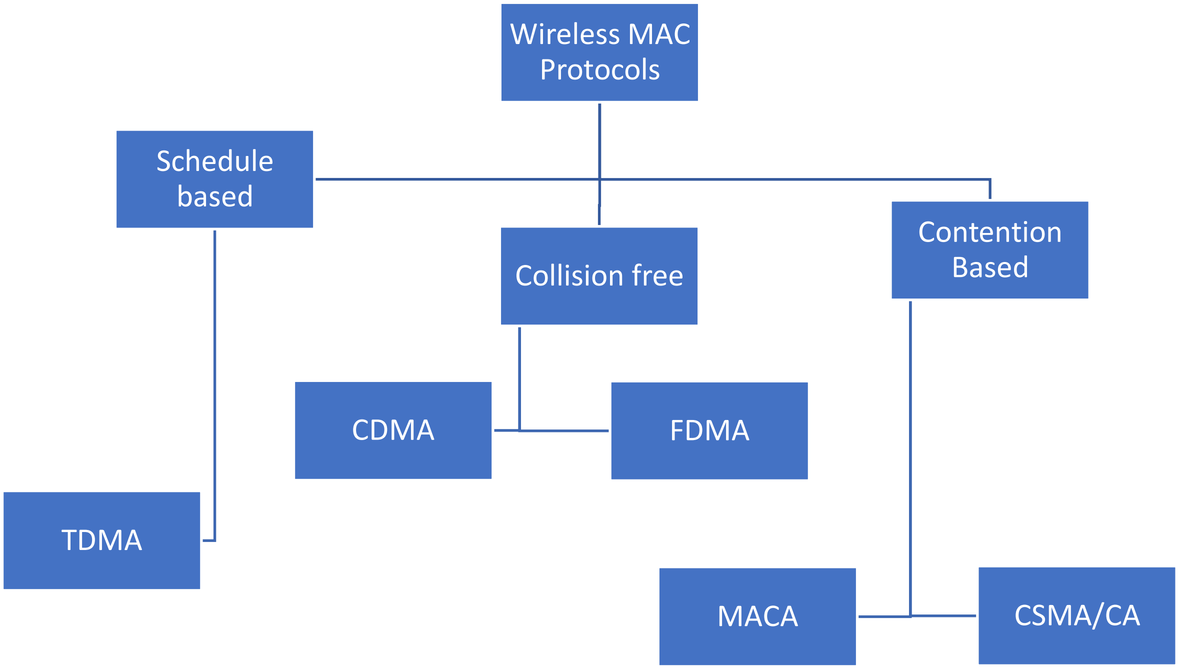


Figure 2.7 - Wireless MAC protocols families (Koubâa, Alves, and Tovar 2005)

The following is the description of each MAC protocol:

a) Scheduling based protocol: This protocol determines the time at which a node can start data transmission using a centralized scheduling algorithm to avoid data packets collision. Time Division Multiple Access (TDMA) is a schedule-based protocol that divides the shared channel into N time slots that allows only one node at a time in each time slot to transmit data.

b) Collision-free protocols: They enable simultaneous data transmission without interference or collisions through using different radio channels for each communication action between two mobile nodes. Moreover, there are two approaches available to achieve a collision free communication, they are, Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA):

i) FDMA: Allocates a part of the spectrum for each pair of communicating nodes by dividing the spectrum into separated frequency bands. This results in a simultaneous communication on different radio channels without collisions between them.

ii) CDMA: This approach allocates the whole spectrum to a node for all the time using unique codes that enables the identification of each communication uniquely among all simultaneous transmissions.

c) Contention-based protocols: This type of protocol's aim is not to avoid collisions but to deal with them and try to minimize their occurrence. Thus, a single radio channel is shared by all nodes on-demand. However, if two or more nodes try to use the shared medium together, a collision would occur. Thus, on the occurrence of a collision, distributed algorithms are used to re-distribute the channel between the competing nodes, reducing their probability of colliding or avoiding its occurrence all together.

Furthermore, according to (Koubâa, Alves, and Tovar 2005; Kleinrock and Tobagi 1975), most MAC protocols follow contention based protocol type that employs carrier sensing and/or collision avoidance mechanisms. This type of protocol is known as CSMA/CA listens to the channel to ensure its idling before initiating transmission. However, if the channel produces a busy tone, the node either waits a random time before sensing the medium or keeps listening until idling is ensured before transmission (Langendoen 2008). Moreover, in multi-hop wireless networks that also uses CSMA/CA hidden and exposed node problems occur. In the hidden node problem, we'll take an example of two nodes S1 and S2 that are not able to communicate with each other due to being out of range between each other. This results, nodes S1 and S2 to sense the medium in a neighboring node B and therefore, because both of the nodes S1 and S2 received idling signal from B and they are not aware of each other's activity, they transmit data together and thus, this results in collision between data packets.

While, in the exposed node problem, we'll take another example with two nodes S1 and S2, and two neighboring nodes R1 and R2. In this problem, when S1 transmits to R1, S2 overhears the transmission and does not transmit to R2 assuming the medium is busy. However, R2 and R1 are not within range of each other and a successful simultaneous transmission would have been possible.

These two case scenarios are presented below in Figure 2.8 for a better visualization:

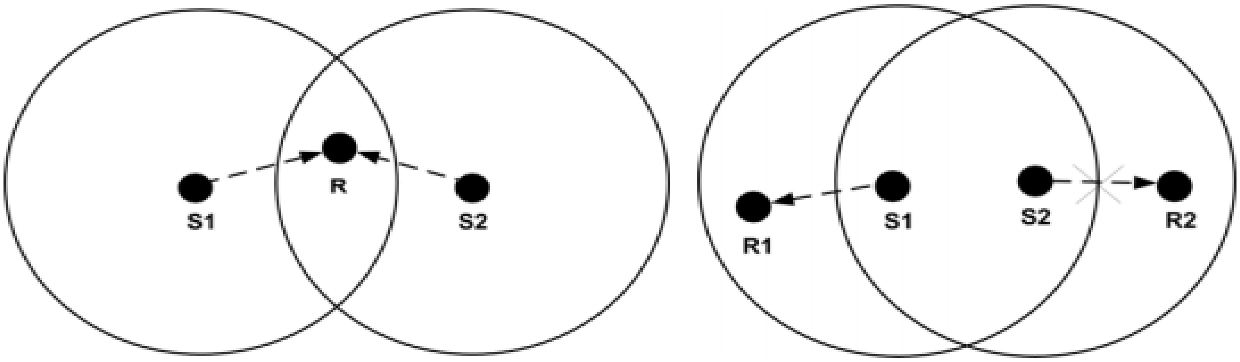


Figure 2.8 - hidden and exposed node problems (Koubâa, Alves, and Tovar 2005)

c) Network layer: The important function of this layer is data routing, allowing communicating open systems establish, maintain, and terminate network connections. All routers at a network are operating at this layer. Moreover, this layer is designed with various principles, according to (Akyildiz et al. 2002) they are:

i. Data centric sensor networks
ii. Sensors with attribute-based and location awareness characteristics are considered ideal
iii. Always consider efficient power consumption
iv. Use data aggregation is only used when it does not hinder the collaborative effort of sensor nodes.

d) Transport layer: This layer is used to access the system by means of internet and other external networks.

e) Application layer: This layer makes the hardware and software of the lower-layers transparent to the sensor network management applications.

2.2.4 Industrial Wireless Sensor Network technologies

Being able to select a suitable wireless technology does not only require the knowledge of the names of existing wireless technologies and their requirements but also a clear definition of each wireless technology, its history, development, recommended applications, etc. is required. According to (Lee, Su, and Shen 2007), The short-range wireless scene is currently held by five protocols, Bluetooth, WirelessHART, ZigBee, ISA100.11a, and Wi-Fi that correspond to the IEEE 802.15.1, 802.15.3, 802.15.4, and 802.11a/b/g standards, respectively. The IEEE standards define the physical (PHY) and medium access control (MAC) layers for wireless communications over an action range of approximately 10-100 meters. Furthermore, the standards WirelessHART and ISA100.11a were developed by the HART communication foundation and the international society of automation (ISA), respectively. Each of the aforementioned have different attributes/features that helps determine their suitability of fulfilling the requirements of different industrial systems in terms of, latency, data rate, jitter, reliability, communication traffic conditions, scenarios/applications, network topologies, Range, bandwidth, etc.

1) BLUETOOTH:

Bluetooth, which corresponds to the IEEE 802.15.1 is based on a wireless radio system designed for short range, cheap communication devices suitable for substituting cables for printers, keyboards, mice, etc. The devices could also be used for communications between portable computers, and act as bridges between other networks, or serve as nodes of ad hoc networks (define) that are considered multi-hop wireless networks where a set of nodes cooperate to maintain the network connectivity (Flammini et al. 2009). This range of applications is known as WPAN (Wireless Personal Area Network). Bluetooth is currently at version 2.0. since march 2004, the IEEE 802.15 working group has adopted the work done for Bluetooth and made it an IEEE standard, namely IEEE 802.15.1 (Ferro and Potorti 2005; Lee, Su, and Shen 2007; Burg, Chattopadhyay, and Lam 2018; Ahmadi et al. 2018). Two connectivity topologies, the piconet and the scatternet are defined in Bluetooth. A piconet, which follows a star topology as shown in Figure 2.4 is a Wireless personal area network (WPAN) formed by a Bluetooth device serving as a master in the piconet and one or more Bluetooth devices serving as slaves (Burg, Chattopadhyay, and Lam 2018; Georgakakis et al. 2010; Pothuganti and Chitneni 2014; Frotzscher et al. 2014). A frequency-hopping channel based on the address of the master defines each piconet. All devices participating in communications in a given piconet are synchronized using the clock of the master slave. Slaves communicate only with their master in a point-to-point fashion under the control of the master. The master's transmission may be either point-to-point or point-to-multipoint. A scatternet is a collection of operational Bluetooth piconets overlapping in time and space. Two piconets can be connected to form a scatternet (Lee, Su, and Shen 2007).

When a Bluetooth device is powered on, it may try to operate as one of the slave devices of an already running master device. It then starts listening for a master's inquiry for new devices and responds to it. The inquiry phase lets the master know the address of the slave. Once a master knows the address of a slave, it may open a connection towards it, provided the slave is listening for paging requests. If this is the case the slave responds to the master's page request and the two devices synchronize over the frequency hopping sequence, which is unique to each piconet and is decided by the master. A Bluetooth device may participate in several piconets up to four piconets at the same time, thus allowing for the possibility of information flowing beyond the coverage area of the single piconet (Willig, Matheus, and Wolisz 2005).

Several types of connections with different combinations of available bandwidth, quality of service, and error protection are defined beforehand by Bluetooth, where the devices can optionally authenticate each other once a connection is established. Roles between master and slaves could be switched when participation in more than one piconet is required (Ferro and Potorti 2005).

Furthermore, Bluetooth devices use the unlicensed 2.4 GHz band also known as the ISM band. There are 79 1MHz -wide channels allocated in most European countries and the united states of America, and only 23 channels in France, japan, and Spain. These are accessed using a Frequency hopping spread spectrum (FHSS) technique, with a 1Mb/s signal rate, and using a Gaussian shaped Frequency Shift Keying (GFSK) modulation. Frequency hopping consists in accessing the different radio channels according to an extremely long pseudo-random sequence generated from the address and clock of the master station in the Piconet and hence, different piconets use different hop sequences (Lee, Su, and Shen 2007).

According to (Willig, Matheus, and Wolisz 2005; Abinayaa and Jayan 2014) there are two different link types defined in Bluetooth, namely Asynchronous connectionless links (ACL) and Synchronous connection-oriented links (SCO). A SCO link provides guaranteed delay and bandwidth, apart from possible interruptions caused by the Link manager protocol (LMP) which have higher priority. A slave can open up to three SCO links with the same master, or two SCO links with different masters, while a master can open up to three SCO links with up to three different slaves. SCO links are suitable for streaming applications that requires a symmetric and fixed bandwidth as they provide constant bit rate, symmetric channels. However, they provide limited reliability as they do not offer retransmissions, and no cyclic redundancy check (CRC) is applied to the payload. Also, an application throughput of up to 0.7 Mb/s or 2.1 Mb/s with enhanced data rate is offered by Bluetooth's physical layer or 3 Mb/s with 8.75 ms minimum cycle time and 7 nodes per network according to (Frotzscher et al. 2014) . Moreover, with the different power classes offered by Bluetooth, a range of 1m up to 100 m could be achieved to accommodate industrial applications. (Burg, Chattopadhyay, and Lam 2018; Rawat et al. 2014).

Furthermore, according to (Burg, Chattopadhyay, and Lam 2018; Lee, Dong, and Sun 2015; Rawat et al. 2014; Christin, Mogre, and Hollick 2010), there are two network types available for Bluetooth. These are namely, Bluetooth Low energy (LE), and Wireless Interface for sensors and actuators network (WISAN). The former has been developed to make up for the energy-efficiency gap between ZigBee and Bluetooth for non-streaming sensor-node-type applications. This gap has been closed through modifying the band rate, number of channels used for frequency hopping, and reducing the application throughput. The later, also uses the Bluetooth's physical layer IEEE 802.15.1 as its basis for wireless interface for sensors and actuators network. Moreover, it is capable of accommodating up to 120 devices in an industrial setting, providing them with reliable, high-speed and low latency connectivity. Devices also have fixed allocated time slots that guarantees latency and low latency channel access.

Thus, with medium data rates and lower energy consumption than the 802.11 standard, IEEE 802.15.1 offers an interesting compromise between energy consumption and data rate, and is therefore particularly suited for high-end applications requiring high data rates as well as applications with strong real time requirements such as Factory Automation (Christin, Mogre, and Hollick 2010).

2) ZigBee:

ZigBee is a specification for a cost-effective, low-rate, and low-power wireless networking technology maintained and published by a group of companies known as the ZigBee Alliance (Lennvall, Svensson, and Hekland 2008; Ahmadi et al. 2018). It is considered a standard for wireless networks with low peak throughput requirements and for short-range application areas such as home networks, remote monitoring, and control (Burg, Chattopadhyay, and Lam 2018; Gomez and Paradells 2010; Zhang and Shin 2011). Its protocol stack is composed of four main layers: the physical layer (PHY), the medium access control (MAC) layer, the network layer (NWK), and the application layer (APL). In addition, ZigBee provides security functionality across layers. Moreover, the physical (PHY) and the medium access control (MAC) layers are defined by the IEEE 802.15.4 standard, and the rest of the stack is defined by the ZigBee alliance. ZigBee is designed to accommodate communication traffic types that are characterized by short irregular bursts with long sleeping periods. This characteristic allows the leaf nodes of the network to operate for multiple months or years on a single battery charge. A ZigBee network can also accommodate a very large number of nodes of up to 65,000 nodes, that can be arranged in either a star, tree, or mesh topology with multiple redundant routers that extends the network range beyond the range of a single point-to-point link (Burg, Chattopadhyay, and Lam 2018; Abinayaa and Jayan 2014; Ahmadi et al. 2018). In addition, All nodes in a ZigBee network share the same channel, and do not use frequency hopping, but only scan for a channel with the least amount of interference at startup (Lennvall, Svensson, and Hekland 2008). Moreover, according to (Lee, Su, and Shen 2007; Rawat et al. 2014) there are two different device types that can participate in a Low-rate-wireless personal area network, a full-function device (FFD), and a reduced function device (RFD). The former can route messages in mesh networks and can operate in three modes serving as Personal Area Network (PAN) coordinator, a coordinator, or a device, and the latter can only communicate with one FFD in a star network setup and is intended for simple applications such as a passive infrared sensor.

Furthermore, according to (Burg, Chattopadhyay, and Lam 2018; Gomez and Paradells 2010; Zheng 2010; Lin, Liu, and Fang 2007) the IEEE 802.15.4 PHY layer used operates in the 868 MHz (with 1 channel) , 915 MHz (with 10 channels), or 2.4 GHz (with 16 channels) ISM bands in Europe, North America, and worldwide respectively, and supports data rates of 20 kb/s, 40 kb/s, and 250 kb/s, respectively with Direct Sequence Spread Spectrum (DSSS) modulation which provides robustness against interference when operating in the crowded 2.4 GHz band. The 2.4 GHz band employs Offset Quadrature Phase Shift Keying (O-QPSK) for modulation, while 869 and 915 MHz bands rely on Binary Phase Shift Keying (BPSK) (Baronti et al. 2007; Tan, Sooriyabandara, and Fan 2011). In addition, the radio range covers a distance of up to 10 to 20m with a transmit power of -25 dBm to 0 dBm with 20 kb/s data rate. Due to Zigbee's bandwidth being lower than the width of the ISM bands, multiple Zigbee networks can co-exist at different frequencies without interference. On the other hand, according to (Willig 2008; Willig, Matheus, and Wolisz 2005; Burg, Chattopadhyay, and Lam 2018; Tan, Sooriyabandara, and Fan 2011), the MAC layer is based on a CSMA protocol and relies either on contention-based random access (un-beaconed) or on a coordinated (beacon enabled) access scheme. In an un-beaconed mode, all stations use an unslotted CSMA variant, where a station does not perform carrier sensing immediately when initiating transmission of a packet, but introduces a random waiting time, called back-off time, which assists the avoidance of collisions. While, the network coordinator in beaconed mode imposes a super frame structure, where it transmits beacons periodically, selecting one of a number of configurable periods between 15.36 ms, and 251.65 s (Willig, Matheus, and Wolisz 2005; Willig 2008).

3) Wi-Fi:

Wi-Fi stands for Wireless Fidelity, which refers to wireless technology that allows devices to communicate over a wireless signal (Tan, Sooriyabandara, and Fan 2011; Ahmadi et al. 2018). Wireless local area networks are omnipresent in home, office, and in industrial environments. It uses waves to allow high speed data transfers over short distances allowing its users to surf the internet at broadband speeds when connected to an access point (AP) or in ad hoc mode. Moreover, the network is based on the IEEE 802.11; including 802.11a, 802.11b, 802.11g, and 802.11n working in either 2.4 GHz or the 5 GHz band dependent on which amendment is used (Li et al. 2017). Different amendments (a/b/g/n) represent the various steps in the standard evolution geared towards enhancing throughput driven by the requirements of different use applications. In addition, the IEEE 802.11 architecture consists of several components that interact to provide wireless Local Area Network (LAN) that supports station mobility with bandwidth frequency that evolved from originally 20 MHz to 40 MHz with the addition of more sophisticated modulation schemes to support data rates between 11Mb/s for IEEE 802.11b up to 144 Mb/s for IEE 802.11n (Burg, Chattopadhyay, and Lam 2018; Tan, Sooriyabandara, and Fan 2011; Ahmadi et al. 2018). Furthermore, with a 20 dBm output power, the systems achieve an outdoor range of 100-200 m or 1-2 floors with decreasing data rates.

According to (Willig, Matheus, and Wolisz 2005), Each of the amendments from the IEEE 802.11x has different features stated as follows:

IEEE 802.11a: is placed in 5 GHz bands that are license exempt in Europe (5.15-5.35 GHz and 5.47 – 5.725 GHz) and unlicensed in the US (UNII bands, 5.15-5.35 GHz and 5.725-5.825

GHz), allowing 21 systems to run parallelly in Europe and 8 in the US. This amendment's physical layer (PHY) is based on the multicarrier system orthogonal frequency division multiplexing (OFDM). It has seven defined modes that ranges from BPSK modulation with rate -1/2 FEC and a 6 Mb/s data rate to 64-QAM modulation with rate -3/4 FEC and a 54 Mb/s data rate. The packet sizes transmitted affects the maximum user-visible rates. For example, an ethernet packet 1500 B long in the 54 Mb/s mode, results in a maximum user rate of about 30 Mb/s, while a 60 B long packet results in a throughput of 2.6 Mb/s, which is a throughput of interest for industrial applications.

IEEE 802.11b: is a high rate extension to the original IEEE 802.11 DSSS mode and thus uses the 2.4 GHz ISM band. Although in principle either 11 (US) or 13 (Europe) different center frequencies can be used for the DSSS, only three systems can actually operate in parallel. In addition to supporting the 1 and 2 Mb/s modulation rates of the basic IEEE 802.11 system, the payload of the IEEE 802.11 system, the payload of the IEEE 802.11b PHY allows for modulation with 5.5 and 11 Mb/s complementary code keying (CCK) (Ferro and Potorti 2005). The maximum user data rates are 7.11 Mb/s in the case of Ethernet packets and 0.75 Mb/s in the case of packets with user payloads of 60 B in length.

IEEE 802.11g: is an extension to the IEEE 802.11b specification and is consequently also placed in the placed in the 2.4 GHz band. It supports four different physical layers of which two are mandatory: the PHY that is identical to IEEE 802.11b and an OFDM PHY that uses the same modulation and coding combinations as IEEE 802.11a. In addition, due to the different frequency bands, the maximum user transfer rates are approximately 26 Mb/s for ethernet packets and about 2 Mb/s for 60 B long packets when using the 54 Mb/s modulation scheme.

Moreover, in contrast to Bluetooth or IEEE 802.15.4, IEEE 802.11 has been specifically optimized to transmit large data files, thus, showing suboptimal performance when the majority of data is made up of short control packets (Ferro and Potorti 2005). In addition, the Wi-Fi MAC protocol, is called Distributed Coordination Function (DCF). DCF is considered a Carrier Sense Multiple Access/Collision avoidance (CSMA/CA) channel access method, that is applied in both ad hoc and infrastructured networks.

4) WirelessHART:

WirelessHART developed by the HART communication foundation was released in 2007 as a wireless communication standard that is suitable for different industrial applications such as process measurement and control applications (Rawat et al. 2014; Zand et al. 2012; Zheng 2010; Khader and Willig 2013; Hassan et al. 2017). It is designed to fulfil certain requirements such as easy to use and deploy, self-organizing, self-healing, flexible, scalable, reliable, secure, and being able to support existing HART technologies such as HART commands, and configuration tools etc., thus, major automation vendors are adopting its technology (Lennvall, Svensson, and Hekland 2008; Zheng 2010). Furthermore, its architecture is composed of four layers, the Physical layer, Data Link layer, Network layer, and Application layer that ensures backward compatibility with already existing solutions (Flammini et al. 2009). Also, it is based on the PHY layer specified in the IEEE 802.15.4-2006 standard; However, it specifies new Data-link, MAC, network, transport, and application layers. In addition, it has an operation frequency of 2.4 GHz and uses 16 different channels with an allowed maximum transmission power of 1Watt in the United States (US), 100 mW in Europe and 10 mW/MHz in Japan (Ovsthus and Kristensen 2014; Zheng 2010). Also, it uses the Time Synchronized Mesh Protocol (TSMP) which was developed by Dust Networks for medium access control and network layer functions which improves reliability using frequency, time, and spatial diversity to access the medium. TSMP uses Time Division Multiple Access (TDMA) based network where all devices are time synchronized and communicates in pre-scheduled fixed length time-slots at 10ms, minimizing collisions and reducing the devices' power consumption (Lennvall, Svensson, and Hekland 2008; Petersen and Carlsen 2011; Khader and Willig 2013). Moreover, to co-exist in the shared 2.4 GHz ISM band and to avoid interference, WirelessHART uses Frequency Hopping Spread Spectrum (FHSS) to hop across the previously stated 16 channels. In addition, Clear Channel Assessment (CCA) is an optional feature that can be performed before transmitting messages, with configurable transmit power level, and a Blacklisting mechanism to ban the use of certain channels (Ovsthus and Kristensen 2014). Moreover, to enhance reliability, WirelessHART supports redundant routing that defines it to be a robust, energy efficient and reliable industrial wireless technology (Lennvall, Svensson, and Hekland 2008). The network topologies supported by the network manager in WirelessHART are Star and Mesh, where star is not recommended (Petersen and Carlsen 2011). In a mesh topology, two different mechanisms are provided, namely, Graph routing and Source routing. Graph routing uses pre-determined paths to route a message from a source to a destination device. Furthermore, a graph route consists of several different paths between the source and destination devices to ensure path redundancy utilization. As for Source routing, it uses an ad-hoc created routes for the messages without providing any path diversity. Thus, making it suitable only for network diagnostics and not for process related messages (Lennvall, Svensson, and Hekland 2008; Flammini et al. 2009; Christin, Mogre, and Hollick 2010).

Furthermore, according to (Petersen and Carlsen 2011; Christin, Mogre, and Hollick 2010), a WirelessHART installation consists of both physical devices and software modules such as a field device, an adapter, a portable handheld WirelessHART computer, a Gateway, a Network manager, and a security manager that are capable of fulfilling one or various functions and all devices are capable of provisioning other devices to join the network. In addition, it has a network scalability limited to the number of devices (50-100) participating which in turn is governed by the available addressing space. Furthermore, for large mesh networks, both network latency and the power consumption of a single device will increase to accommodate all the communication links in the network. As for the maximum achievable data rate, it is proportional to the number of devices in the network. A combination with offset-quadrature phase shift keying (O-QPSK) modulation allows for a raw bit rate of 250 kb/s. In addition, a maximum transmitted power is limited to 10mW (=10dBm), giving most devices an outdoor range of up to 100m with direct line of sight, depending on the sensitivity of the Radio Frequency (RF) receiver.

Moreover, for the successful adoption of WirelessHART in the process automation and manufacturing industries, it is imperative that the technologies are capable of coexisting with other wireless technologies such as Bluetooth, etc. operating on the same 2.4GHz band. Since IEEE standard 802.11 defines a total of 14 channels in the 2.4 GHz band, with each channel being 22 MHz wide, and 5 MHz spaced apart, it has become common in industrial deployments to configure WLAN access points to use the non-overlapping channels 1, 6, and 11. Thus, relative interference-free operation of WirelessHART can only be achieved in channels 15, 20, and 25 (Hassan et al. 2017).

5) ISA100.11a:

The ISA100.11a standard has been developed by the ISA 100 standards committee which is part of the non-profit International Society of Automation (ISA) organization and approved by the ISA Standards and Practices Board in September 2009. Furthermore, according to (Willig 2008; Ovsthus and Kristensen 2014), its first release focused on process applications that tolerate delays up to 100ms . However, according to the recent analysis of (Raza et al. 2017), ISA100.11a recently targets monitoring, automation and process control applications in an industrial setup. Moreover, In ISA100.11a, a set of roles are defined to describe the functions and capabilities of a device. An ISA100.11a device shall hold one or more of these roles (Wang 2011; Nixon and Rock 2012; Raza et al. 2017):

1**) an Input/Output (I/O) device:** provides sensed data to or uses data from other devices.

2**) A router:** A routing device that routes data from other devices in the network.

3**) A provisioning device:** provisions other devices, enabling them to join the network.

4**) A backbone router:** A routing device that routes data to/from a backbone network.

5) **A gateway device:** provides an interface between wireless and the plant network or directly to an end application on a plant network.

6) **A system manager:** An application that governs the network, network devices, and network communications.

7) **Security manager:** An application that, in conjunction with the system manager, provides a secure system operation.

8) **System time source:** A device that is responsible for maintaining the master time source for the system.

According to the aforementioned, the components in an ISA100.11a network consists of field device, backbone routers, gateway, system manager, and security manager. Thus, for ISA100.11a, the sensor and actuator roles (I/O) are separated from the router role. This enables ISA100.11a field instruments responsible for sensor data collection and actuator management and able to provide routing functionalities to allow the ISA100.11a network to employ a star, star-mesh network, or mesh topologies. In addition, according to the standard, there are no limitations to the amount of subnets that form the network which means there are no limits to the total amount of devices; however, there is a limit of having up to 30,000 devices per subnet (restricted by the addressing space) with an operation period that ranges from 10 to 12 ms (Christin, Mogre, and Hollick 2010; Petersen and Carlsen 2011; Quang and Kim 2013).

Moreover, The ISA100.11a standard addresses all the Open System Interconnection (OSI) layers including physical, data link, network, transport, and application layers. similar to WirelessHART, the ISA100.11a follows the IEEE 802.15.4 standard on the physical layer, and thus, has similar characteristics such as low data rates that reaches 250 kb/s, the use of channel hopping and channel blacklisting to reduce interference, etc. However, according to (Ovsthus and Kristensen 2014; Willig 2008; Christin, Mogre, and Hollick 2010), the ISA100.11a only supports the frequency band at 2.4 GHz and does not support the lower sub-bands.

ISA100.11a divides the Data Link Layer (DLL) into a MAC sublayer, a MAC extension, and an upper DLL. The MAC sub-layer uses Carrier Sense Multiple Access/Collision avoidance (CSMA/CA) mechanism for the channel access with an optional implementation of IEEE 802.15.4, CSMA/CA based exponential back-off mechanism available. This mechanism allows the implementation of TDMA based channel access and channel hopping. Furthermore, ISA100.11a applies different methods for channel hopping like slow hopping, fast hopping/slotted hopping, and mixed hopping/hybrid hopping in the 16 frequency channels offered by IEEE 802.15.4 in the 2.4 GHz ISM band in the Data Link layer. The data link layer is responsible for the management of the employed Time-division multiple access (TDMA) schemes by configuring the timeslot durations and managing the superframes (Hassan et al. 2017).

As mentioned, there are two different patterns at which configuration of the timeslots can be done: slotted channel hopping and slow channel hopping. The former scheme optimizes the bandwidth utilization and is adapted to energy-constrained routers, where each timeslot uses the next successive (different) radio channel in the hopping pattern. Additionally, it is used in the communication of which timeslots are allocated explicitly and is utilized in the communication scenarios where tight synchronization is crucial or transceiver is energy-limited. While the latter smooths the time synchronization requirements between neighbors powering their receivers continuously during well-defined periods. Also, slow hopping is occupied by successive timeslots with a slow hopping duration being typically 100-400 ms and designated by the system manager. Usually, channels 15, 20 and 25 are designed as slow hopping channels and could be used when loose requirement of synchronization is required, to support devices with imprecise timing settings, devices that lost contact with the network, or when energy for running a transceiver of the device is enough for a period of time (Wang 2011). Moreover, as also mentioned previously, both patterns can be combined in a hybrid fashion by mixing superframes together where slotted hopping accommodates scheduled and periodical messaging, and then slow hopping less predictable messaging such as alarm and retries. (Christin, Mogre, and Hollick 2010; Nixon and Rock 2012; Raza et al. 2017; Wang 2011).

In addition to managing the TDMA, the network manager assigns paths and links between the devices composing the Wireless Sensor Networks (WSNs) as each link is associated to one or multiple timeslots of a superframe and its type can transmit and/or receive information about the neighbors, the channel offset from the superframe hopping scheme, and possible alternatives for the transmission and reception which is considered/called graph routing scheme. Moreover, the ISA100.11a data link layer supports source routing, which is a single directed route between a source and a destination device, where a specific path that the packet has to take when travelling from its source to its destination is defined. However, if a single link in a source route fails, the packet is lost, while in a graph route, each device will have multiple associated neighbors to which they may send packets, thus, ensuring redundancy and enhances reliability. The routes are configured by the system manager based on the periodic reports from devices indicating historical and instantaneous quality of the wireless connectivity to their neighbors (Wang 2011; Rezha and Shin 2013)

As for the network layer, it provides schemes for routing and quality of service (QoS) derived from 6LoWPAN, allowing the use of IPv6 addressing. Also, Packet fragmentation and reassembly are ensured at this layer. The packets can be routed at the backbone and the mesh levels, as defined in the standard. Moreover, depending on the level of reliability, the ISA100.11a transport layer can support end-to-end acknowledgements as well as unacknowledged communication. The transport layer also supports flow control, segmentation, and reassembly. As for the application layer, it ensures standard interoperability by using tunneling and native protocols at the gateways. Hence, the former carry protocols used in existing standards such as HART or FOUNDATION Fieldbus, while the latter provide efficient bandwidth utilization and therefore increase the battery lifetime.

In conclusion, the ISA100.11a standard operates in the 2.4GHz band, using DSSS and FHSS combined with O-QPSK modulation techniques, giving a maximum raw data rate of 250 kb/s. Furthermore, its maximum transmitted power is regulated by governing bodies and limited to 10mW, allowing a transmission range of up to 100 m. Finally, TDMA with frequency hopping is used for channel access, and they both employ self-configuring, self-healing mesh networks with redundant paths and ACK-based packet retransmissions. With these qualities, ISA100.11a standard should be capable of robust and reliable communication in harsh industrial environments (Petersen and Carlsen 2011; Willig 2008).

2.3 Industrial Systems

There exists a broad spectrum of Industrial systems today that are designed to complete certain tasks and to be implemented in certain divisions such as Hospital, military, and industrial etc. In the past decades, Industrial automation has been developed worldwide into a very attractive research area. It incorporates different modern disciplines including communication, information, computer, control, sensor, and actuator engineering in an integrated way, leading to new solutions, better performance and complete systems. One of the most important components in the industrial automation is the industrial communication (Norstrom and Hansson 2005). Thus, for interconnection purposes, an industrial automation system can be combined with various sensors, controllers, and heterogeneous machines using a common message specification (Lee, Su, and Shen 2007; Pothuganti and Chitneni 2014).

To further address the topic, wireless technologies in manufacturing industries and the industrial wireless sensor networks available that copes with the projected market trends that meets the crucial deadlines in highly sensitive industrial atmospheres are studied and reviewed. Thus, a clear identification and categorization of the available industrial systems, communication traffic generated in them according to priority requirements, deadlines for selected industrial processes, existing work, standards, and industrial protocols is obtained. According to the International Society of Automation (ISA), the industrial systems can be distributed into six classes based on the nature of application, standard operating procedure, access schemes, reliability, and latency requirements(Zand et al. 2012; Raza et al. 2017). These systems are listed below:

1) **Safety/Emergency Systems:** handle issues of greater significance and critical nature. Action on developed situations are required in matter of milliseconds (ms). Any added delay can contribute to unwanted complications

2) **Close Loop Regulatory Control Systems:** require a periodic feedback for smooth running of the processes. Such systems include both sensor and actuator elements where continuous feedback from the sensors is needed to maintain the desired response of the actuation part. Usually time bounds between sensing values and making the desired corrections using actuators, based on the sensed values, are very low. Examples include, autonomous cars, motion adaptation for conveyor belt movements and affiliated robotics etc.

3) **Close Loop Supervisory Systems:** provide feedback control like the regulatory systems, except, these systems are asynchronous in nature and a feedback mechanism is established when certain thresholds are violated. Since, these systems are less critical in nature compared to regulatory control systems, time and reliability bounds are more relaxed. Examples include, slow changing and less critical processes such as temperature control of a furnace or boiler, etc.

4) **Open Loop Control Systems:** They implement human operated process control. These systems, instead of automated analysis, rely on human intervention, where the operator after analyzing the sensed data, takes the necessary action.

5) **Alerting systems:** Provide feedback of the sequential processes where regular or prompt feedback of the sequential processes where regular or prompt feedback is established as a surety mechanism. They offer tracking mechanism with regular feedbacks for different stages of the processes. In some cases, event-based alerting is also established.

6) **Information gathering systems**: used to collect sensor reading regarding non-actionable processes. The data gathering is targeted to provide the pattern observations over long period of time, which can serve as a baseline for the future changes and implementing long term

plans. Information gathered in such systems is considered non-critical in nature, therefore, the data accumulation phases can span days.

2.3.1 Industrial Systems' Communication Traffic Types

In industrial systems, there are different application areas, and due to the different types of systems available and defined above, there exists different types of communication traffic accordingly. There are different research papers that provided different categorizations for the communication traffic types available, such as (Zheng, Gidlund, and Åkerberg 2015; de Moraes and Silva 2014; Shen et al. 2013; Raza et al. 2017). However, the most descriptive and simplified categorization was provided by (Raza et al. 2017). In this paper, there were six groups that defined the different types of communication traffic in industrial systems setups, they are, safety/emergency, regulatory, supervisory, open loop control, alerting, and monitoring communication traffic. These categories are explained in detail below:

a) safety/emergency communication traffic: highest priority communication traffic that may threaten a human life or incur damages to a plant if mis-handled. It is considered asynchronous and is infrequently triggered in irregular situations such as in risks of explosion and when severe electrical surges occur. Therefore, it is expected to have high reliability and fail-safe links established with multiple contingencies. This type of communication traffic has highest priority and thus, requires prioritized access to communication channel.

b) Regulatory control communication traffic: it is the communication traffic originated from systems running close loop regulatory controls. These types of systems extremely contribute in density of the IWSNs communication traffic. This is due to high sensors sampling rate and generation of periodic information by those systems. Furthermore, these systems aim to reduce the dead-time between two consecutive communications to achieve optimistic performance. Thus, ignoring/delaying of such communication traffic may result in triggering the emergency switch. Moreover, this communication traffic type is considered to have synchronous information load that occupies constant bandwidth; this Therefore, this type of communication traffic has the second highest priority after the emergency communication traffic as failure in communication can result in instability of the process control.

c) Supervisory control communication traffic: similar to the regulatory control communication traffic type; however, unlike its synchronous attribute, the supervisory control communication traffic is asynchronous in nature. Thus, localized processing is used as an identification strategy to ensure specified thresholds are not violated. Thus, based on this identification, priority level is assigned. The behavior in this communication traffic type can either be related to regulatory control or asynchronous alerting communication traffic based on its less critical nature and depending on the conditions (Zand et al. 2012; Shen et al. 2013). Moreover, when the communication traffic type is deemed critical, information is regularly reported from sensory data to control center and requires a higher level of reliability. While, in less critical cases, asynchronous communication is established with reduced reliability requirements (Raza et al. 2017)..

d) Open loop Control communication traffic: according to (Raza et al. 2017; Zand et al. 2012), it is considered a low risk type of communication traffic that is flexible with time and reliability constraints. This is because of the slight impact it would have on the process control application due to a failure of any communication. Moreover, it is a human dependent response system that mainly report information to the control unit to be analyzed by a human operator.

e) Alerting communication traffic: according to (Zand et al. 2012) this type of communication traffic follows a relatively low duty cycle due to dealing with a limited amount of information.

Irregular conditions may cause an increase in the frequency of data communicated. Thus, in such cases, criticality and reliability of communication traffic requirements increase accordingly to become similar to those of emergency communication traffic requirements. However, if that is not the case, lower reliability would be required as data communication failures would not impact the system severely (Zheng 2010; Raza et al. 2017).

f) Monitoring communication traffic: according to (Zand et al. 2012; Shen et al. 2013), this type of communication traffic is considered a single way communication traffic as it is not usually used to control and automate the processes but only monitor them. Data monitored and collected are used to predicate futuristic system upgrades and improvements (Raza et al. 2017).

2.4 IWSN/Decision Recommendation Tool

One of the commonly used tools that support decision making when multiple criteria are involved is the Analytic Hierarchy Process (AHP) tool. It is a structured technique that organizes and analyses complex decisions, mathematically and psychologically (Saaty 2008). Also, AHP is a flexible tool that can be applied to any hierarchy of performance measures (Rangone 1996). Moreover, to make a decision in an organized way, both (Saaty 2008) and (Chou and Liang 2001) suggested a four step strategy that utilizes AHP: 1) Define the problem and determining the kind of knowledge sought, 2) collect and analyze useful criteria information, 3) choose the appropriate method, and 4) evaluate the alternatives.

Furthermore, the success of AHP in various research areas such as transport systems, job attractiveness, maturity models, shipping companies' performance, etc. proves its decision-making problems solving abilities. Some of the work implemented by different researchers that utilized AHP include, but are not limited to, selecting environment friendly support systems in India by (Yedla and Shrestha 2003), studying job attractiveness in the airline Industry in Taiwan by (Lirn et al. 2004), creating a model capable of evaluating the performance of shipping companies by (Chou and Liang 2001), etc. Consequently, according to (Forgionne, Kohli, and Jennings 2002), the decision support system mechanism implied through the AHP methodology is adaptively capable to be modified to accommodate different models through sensitivity analysis. Therefore, the six-step methodology proposed in the thesis to recommend the most suitable IWSN technology, requires a decision-supporting tool to successfully achieve this goal.

2.5 Research Gaps

In this section, a vast amount of research directed towards evaluating the performance of different wireless sensor technologies, comparing their attributes and selecting where they would best fit in meeting the different industrial system requirements were reviewed. Based on the 2020 IEEE taxonomy report (IEEE 2020), which comprises the first three hierarchal levels under each term-family formed from the top-most terms in the IEEE thesaurus, the term wireless sensor networks, is considered as the first level under both, the wireless technologies family term and under the communication technologies family term. Thus, illustrating the importance of advancing in research in this area due to lack of research relative the importance of the topic.

From this review, a research gaps table is shown in Table 2.1. To begin, research on wireless technologies has not covered an optimal wireless technology recommendation/selection methodology that could be implemented on any industrial system used in specific application areas. In addition, there was a lack of coverage of the types/classes of industrial systems, their relevant application areas, and their essential communication requirements needed for a successful wireless technology selection and implementation.

Starting with (Wang 2011), the author researched and identified the differences between two wireless technologies, namely WirelessHART and ISA100.11a in regards to their network architectures, functionalities of protocol layers and network operations, to produce an evaluation report to suggest which of the two research wireless technologies would best fit industrial automation applications, and specifically process automation applications through analyzing their differences from system architecture to each protocol layer's functionality. The result of the evaluation favored ISA100.11a. However, in the author's evaluation, no specific industrial applications, scenarios, actual data or mathematical models were considered.

In addition, (Alcácer and Cruz-Machado 2019) reviewed the enabling technologies of I4.0 specifically, the concept of smart factory. The authors stated that the key technologies of I4.0 are the Industrial Internet of Things (IIoT), cloud computing, big data, simulation, augmented reality, additive manufacturing, autonomous robots, and cybersecurity. The authors also stated that the integration of I4.0 has two major characteristics relying on vertical and horizontal communication integration. Moreover, the authors highlighted the focus of I4.0 to be towards establishing intelligent and communicative systems and dealing with the data flow between the industrial system referring to the common IoT architecture having four main layers that are sensing, networking, service, and the interface layer. The authors work only provided an overview of key enabling technologies of implementing I4.0, including the importance of wireless sensors and IWSNs, however, did not provide any selection methodology that assists in implementing them.

In (Schütze, Helwig, and Schneider 2018), the authors provided a comprehensive review of the importance of smart sensors and their development in analogy to I4.0, highlighting their potential and requirements needed for further development. Their work discussed condition monitoring and data analysis in manufacturing processes, stating the importance of acquiring self-diagnostic capabilities in a manufacturing system, the different types of sensors, and their application areas. Moreover, the authors presented a new measurement paradigm of condition monitoring using data-based modelling, where the system status is evaluated based on several thousand cycles of data from existing sensors, to test and improve the overall performance of the system. The authors work emphasized the importance of sensors and communication factors that affect their performance such as frequency, transmission range and latency not only in industrial processes but also in different areas such as smart cities and smart mobility. However, their work only considered smart sensor devices and did not consider the wireless network types or specific numerical communication requirements according to system class and application scenario identification. The authors work also lacked providing a selection methodology of how to select a suitable IWSN that fits specific I4.0 system requirements to enhance the overall performance of the system.

Moreover, (Zand et al. 2012) provided an overview of existing wireless technologies such as ZigBee, WirelessHART, and ISA100.11a etc. used in process automation industries, specifically in monitoring and control industry. The authors assessed the degree to which each technology was able to meet the industry's demands through theoretical identification of different classes of applications defined by ISA. However, their research lacked numerical data of different system requirements and wireless technologies properties. Moreover, there was no selection methodology used to assess the suitability of each wireless technology studied.

(Candell et al. 2018) presented a comprehensive guide to select and implement wireless technologies in an industrial environment. In their guide, the authors stated the factors, such as data rates, latency, transmission range and network topologies, etc. that should be considered before deciding. In addition, the authors considered factors related to the industry such as the industrial applications, and industrial equipment requirements. Furthermore, the authors only presented general numerical requirements for different industrial applications. However, the authors work lacked consideration of specific industrial equipment requirements, specific IWSNs properties, and engineering manufacturing scenarios that enable determination of IWSN technology suitability.

Furthermore, Zhao (Zhao 2011) provided a survey on wireless sensor technology implementation in process automation industry. The author briefly reviewed different classes that process automated applications would fall in without presenting their numerical data requirements. Next, the author provided theoretical solutions to improve accuracy and integrity of communicated data. However, the author failed to provide a selection strategy that helps the user select a suitable wireless technology.

Moreover, (Anand, Moyne, and Tilbury 2009), studied both Wi-Fi and Bluetooth wireless standards also known as IEEE 802.11a,b,g and IEEE 802.15.1 relatively. They highlighted the performance aspects of both standards relevant to control and automation to demonstrate that they could be used for control systems. They conducted a performance evaluation experiment in a factory environment where no other nodes were competing for the channel (no-interference), and with interference. Their performance results showed that the standard IEEE 802.11a (Wi-Fi) is the best fit. However, the authors failed to include other wireless technologies in their experiment and did not consider actual industrial system communication requirements. Also, they did not consider the different scenarios and equipment within an industrial system.

In (Hayashi, Hasegawa, and Demachi 2009), the authors reviewed three different wireless technologies: ZigBee, ISA100.11a, and WirelessHART. However, the authors performed a comparative study only between ISA100.11a and WirelessHART, stating their network layers, features, etc. The authors also provided a brief review of other features within wireless sensor networks such as frequency hopping, mesh networking, and channel backlisting. The end result did not include a recommendation/selection of any of the compared technologies. Moreover, the authors did not include any information about industrial requirements, applications, and numerical data for the wireless technologies' properties, and industrial requirements.

Furthermore, (Raptis, Passarella, and Conti 2019) provided a comprehensive survey that discussed data management in networked industrial environments, dividing them into two different categories that are data enabling industrial technologies and data-centric industrial services. Under both categories, the authors listed the recently researched articles on I4.0 technologies. Some of the articles relating to this thesis included Wireless Sensor Actuation Network (WSAN), IIoT, industrial robots, machine to machine communication, big data analytics, etc. Furthermore, they stated the different use cases, technologies, and services that can facilitate their management. The authors mentioned that wireless technologies are emerging and are integrated in the manufacturing landscape exponentially, discussed and compared their key aspects, such as latency, data rates, topologies, etc., in relation to each article in the aforementioned data management classifications. In addition, their work considered four of the most popular wireless technologies according to them, namely: Zigbee, WirelessHART, ISA100.11a, and WIA-PA. However, although the authors work emphasized the importance of communication reliability and stated several communication improvement methods such as network topology, data routing, specific application consideration, etc., it lacked any identifications of specific numerical or theoretical industrial communication requirements for specific industrial equipment's, manufacturing scenarios to be considered, and did not propose a selection strategy to determine a suitable IWSN technology.

In (Frotzscher et al. 2014), the authors provided an overview on industrial applications requirements, specifically control of automated applications, and current wireless technologies that could meet them, and presented a comprehensive review of future industrial requirements. The research included a comparison of numerical parameters for both industrial requirements (closed-loop control) as it has the most stringent requirements, and some of the wireless technologies such as Wi-Fi, Bluetooth, etc. However, the research did not provide a recommendation/selection of a specific wireless technology and did not include all types of industrial systems and relevant applications.

In (Flammini et al. 2009), the authors provided an overview of the state of art real time sensor networks for industrial applications. Also, the authors presented equations for performance evaluation. However, the authors did not include any wireless sensor networks in their evaluation, neither did they include any numerical properties of wireless technologies and specific system requirements to provide a recommendation/selection of a specific wired/wireless technology.

In (Petersen and Carlsen 2011), the authors, provided a comparative study between WirelessHART and ISA100.11a. The authors also, provided an overview of both technologies' system overview, communication protocols, their suitability in industrial automation. Furthermore, the authors concluded that more research might be required for both technologies to determine the most suitable, yet, suggested that ISA100.11 would perform better. However, the study lacked industrial systems requirements' identification, other wireless technologies and their relevant properties.

In (Abinayaa and Jayan 2014), the authors conducted a comparative study between Wi-Fi, ZigBee and Bluetooth with respect to their standard, bandwidth, battery life, data rate, and maximum transmission range. The authors concluded their study by recommending ZigBee over the other wireless technologies. The research lacked industrial systems requirements consideration in different applications. Also, the research lacked a selection methodology.

2.6 Conclusion

Several research gaps were identified from the literature review and are presented in Table 2.1.

Table 2.1 - Research gaps table

Authors	**Selection strategy**					**Factors Studied/considered**						**IWSN technologies considered**					Ind. equipment manufacturing scenarios	Industrial application
	Performance evaluation	comparative	Simulation	AHP	No selection	Data rates	transmission range	bandwidth	Frequency range	MAC	Industrial system req.	ZigBee	Bluetooth	Wi-Fi	WirelessHART	ISA100.11a		
(Wang 2011)	x									x					x	x		
(Alcácer and Cruz-Machado 2019)					x							x	x	x				
(Shutze et. al. 2018)					x	x	x		x		x							x
(Candell et al. 2018)					x	x	x		x	x	x	x			x	x	x	x
(Anand et. al 2009)	x					x			x				x	x				
(Ovsthus and Kristensen 2014))		x								x	x				x	x		x
(Raptis, Passarella, and Conti 2019)					x					x	x	x			x	x		
(Frotzscher et al. 2014)	x	x				x	x	x					x	x				
(Flammini et al. 2009)	x		x							x								x
(Petersen and Carlsen 2011)		x				x	x	x	x	x					x	x		x
(Abinayaa and Jayan 2014)		x				x	x	x	x			x	x	x				x
This thesis				x		x	x	x	x	x	x	x	x	x	x	x	x	x

In conclusion, the table above presented a variety of researchers' work related to wireless sensor network technologies. The authors' work included reviews of different wireless sensor technologies and industrial systems' classes, their properties, and some applications. Moreover, the work reviewed included performance evaluations, network simulation, and some included theoretical comparative studies. However, their work was lacking the consideration of all the available wireless sensor technologies, their numerical network properties including data rates, topologies, Medium Access Control (MAC) protocols, range, etc., the different types of the industrial systems' classes, their numerical network properties including their communication traffic types and relative latency constraints, data rates, range, etc. In addition, none of the work reviewed presented a wireless sensor network selection methodology. Thus, the work presented in this thesis, covers this gap through presenting a wireless sensor network selection methodology that utilizes Analytic Hierarchy process (AHP), creating a tool that takes into consideration the different industrial systems' classes, communication traffic types, communication requirements, the state of art wireless sensor network technologies, and their communication properties, all together, providing a wireless sensor network technology recommendation that fits an industrial system's requirements.

CHAPTER 3

WIRELESS SENSOR TECHNOLOGY SELECTION FOR I4.0 MANUFACTURING SYSTEMS

3.1 Overview

The current market is developing an everchanging customer demand towards product customization and personalization, etc. This change requires manufacturers to implement new technologies and manufacturing strategies to fulfill the customer requirements. Thus, researchers are motivated to research different types of industrial systems, their requirements, and application areas. Therefore, an extensive research has been carried out on a methodology for selecting a wireless technology to meet the requirements of different industrial systems in different application areas. Most research is concerned with developing different MAC protocols and routing mechanisms to achieve optimized performance for certain wireless technologies through mathematical modelling and simulations. These mathematical models and simulations are based on many assumptions that do not match real life industrial environment case scenarios and can lead to infeasible solutions. Moreover, there is a lack of research in providing a selection methodology to select a suitable wireless technology for a certain class/type of industrial system taking into consideration the industrial systems' requirements in specific application areas/scenarios, and the properties of different wireless technologies.

3.2 Introduction

In the present day, large scale industrial monitoring and control systems may consist of an enormous number of sensors, controllers and actuators. However, it is essential for the devices to communicate accurately/efficiently to perform their assigned tasks. In the past, wired systems that used point to point communication strategies were used. However, it has become inconvenient due to the amount of wires used, connectors and wire harnesses involved in the process. Moreover, industrial processes are rapidly increasing in complexity in terms of factors such as scale, quality, inter-dependencies, etc. for example globalization has led companies to open manufacturing plants in multiple geographic locations. Yet, it is essential to have a detailed outlook of the various operational characteristics of every single piece of equipment within every industrial plant to optimize the efficient utilization of a wireless sensor network (wireless industrial monitoring the journey so far). IWSNs have emerged as an efficient and cost-effective solution for industrial automation and process control. They have many advantages associated to them such as their low installation cost, scalability, flexibility, self-organization, localized processing, interoperability and easy deployment (Shahzad and Oelmann 2014). However, with every new technology that arises, there has to be some disadvantages. With the IWSNs, the disadvantages are divided into two categories, critical and non-critical. Both types are tentative to the situation, type of industry, and application of where the IWSNs are being deployed/used. The disadvantages include, constrained communication, small memory, delay, limited bandwidth, reliability issues, limited battery capacity, security threats and interconnectivity. Each of the aforementioned, can be critical to the system or non-critical. For example, considering two application scenarios where in one case, the temperature sensor is used in fractional distillation of crude oil and the other involves the operational temperature of pressurized flammable gases. The former is much more variation tolerant than the later as for fractional distillation some significant temperature variations can increase the level of impurities in different distilled oil products, which is undesirable but not hazardous. However, in case of dealing with pressurized flammable gases, the temperature variations are much more sensitive and can even cause fire. Therefore, in dealing with flammable gasses, more frequent feedback is required as the delay of data transferred is considered very critical in comparison to the delay of temperature data transfer in case of fractional distillation. Thus, we have same sensors that are used for two different applications and with two criticality conditions, one being critical and the other non-critical.

Therefore, to avoid a critical or non-critical and to achieve efficient communication between different industrial systems in an industrial environment, an accurate selection methodology is developed that uses an Analytic hierarchy process (AHP) calculator that evaluates different IWSN technologies to perform an IWSN technology selection ensuring a fulfillment of the manufacturing industry’s requirements.

3.3 Methodology and Tool Development

A clear identification and analyzation of the problem is required in order to develop a selection tool. Thus, the next section presents an overview of the IDEF0 tool. It is used for the selection tool. However, in this section, a methodology is presented to demonstrate the steps required to achieve a selection methodology.

To determine if a wireless technology is suitable, a clear identification of the industrial system class it is applied to, its application area, and requirements is needed. Thus, a clear tabulated categorization of the different industrial classes available, the different application areas and industrial systems potentially available, and their respective requirements is needed. Moreover, a clear identification of the different industrial wireless sensor network (IWSN) technologies applicable is required, along with their properties that could be mapped to the industrial system’s requirements is also needed. Hence, presented below is the step by step methodology to achieve an accurate IWSN selection for an industrial system in an industrial environment.

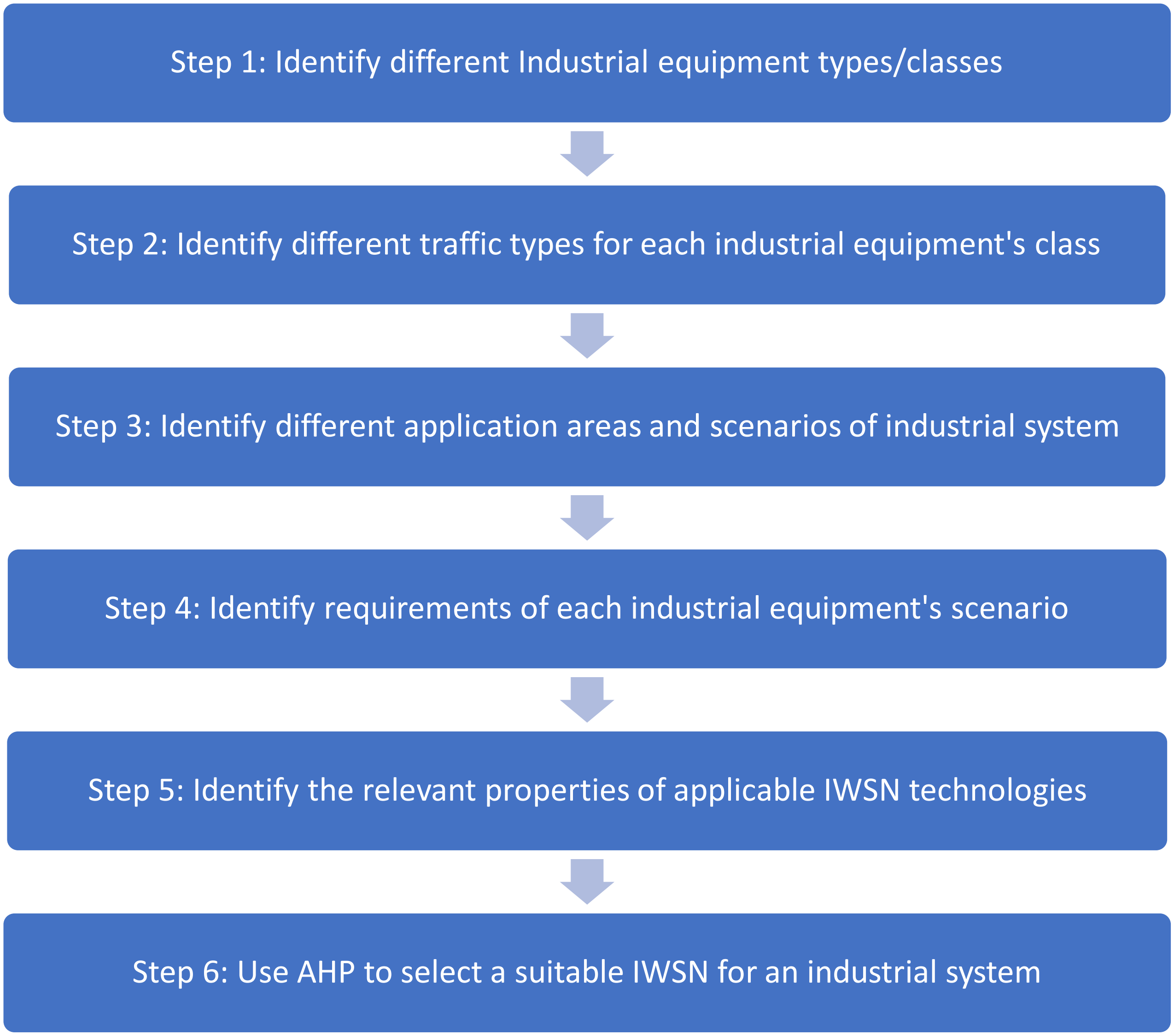


Figure 3.1 – 6 step Industrial Wireless Sensor Network technology selection methodology

3.3.1 IDEF0

The definition for function modeling (IDEF0) approach distinguishes between inputs, outputs, mechanisms, and constraints, shown in Figure 3.6. The model requires four inputs, the Industrial systems' classes and communication traffic types, industrial systems' application areas and scenarios, the industrial systems' requirements, and finally, the IWSN technologies and their respective properties. For this thesis, five IWSN technologies were studied, each of them is applicable in an industrial environment.

The mechanisms/tools used in the model are data collection of the factory's industrial equipment to identify their manufacturing process and their service area. The second mechanism is the Analytic Hierarchical Process (AHP) decision support technique. AHP is a decision-supporting technique that performs pairwise comparisons to measure the relative importance of elements at each level of a hierarchy. In this case, it is utilized in an excel sheet ready tool where: i) it measures the relative importance of each industrial equipment to other equipment in an industrial system, ii) it measures the relative importance of each communication requirement relative to each industrial equipment, and iii) it considers the relative importance of the properties available in the five IWSN technologies relative to the communication requirements, which then provides a recommendation to the user of the most suitable IWSN technology based on the rank provided through AHP.

In addition, there are two model constraints, which are the time it takes the user to obtain the required data, and the different costs associated for implementing/installing the IWSN. The cost is represented with a dashed line because, although it is a very important decision-making factor to be considered when selecting the most suitable IWSN, it is not being considered in this thesis due to the availability of large number of wireless sensor devices with various prices and energy consumptions depending on the various factory sizes and number of sensor nodes required, hence, it is difficult to obtain an approximate/generic implementation cost. Therefore, this is left to the user to finalize the selection accordingly.

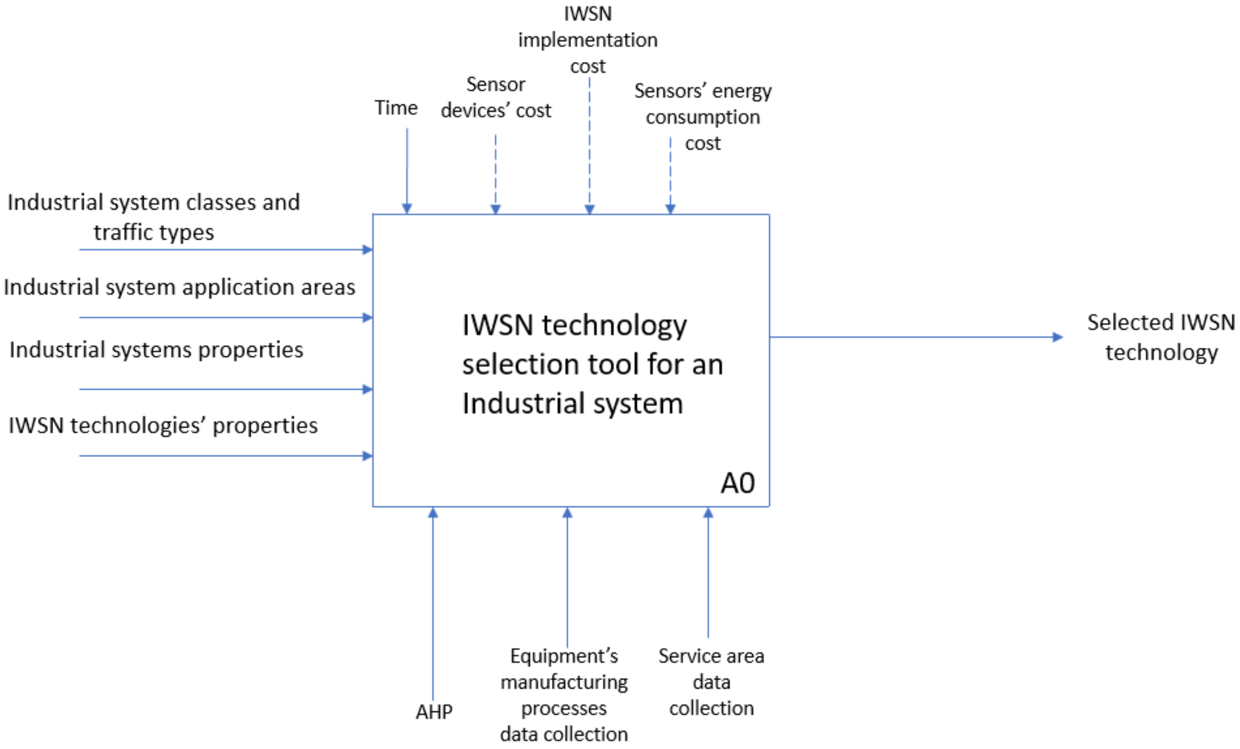


Figure 3.2 - IDEF0 for IWSN technology selection

3.3.2 Industrial system classes and communication traffic types

As mentioned before in section 2.3, Industrial systems are categorized into six classes, where each class has a corresponding communication traffic type. Identifying and categorizing the different class types and their relevant communication traffic types provides the user with the knowledge of identifying the level of criticality of the industrial system at hand. The user can then determine the reliability and time requirements when providing relative importance weights in the Analytic Hierarchy Process (AHP) tool. Thus, presented below, is the tabulated form Table 3.1 of the different industrial system classes and their corresponding communication traffic types:

Table 3.1 - Industrial systems' classes and communication traffic types (Raza et al. 2017):

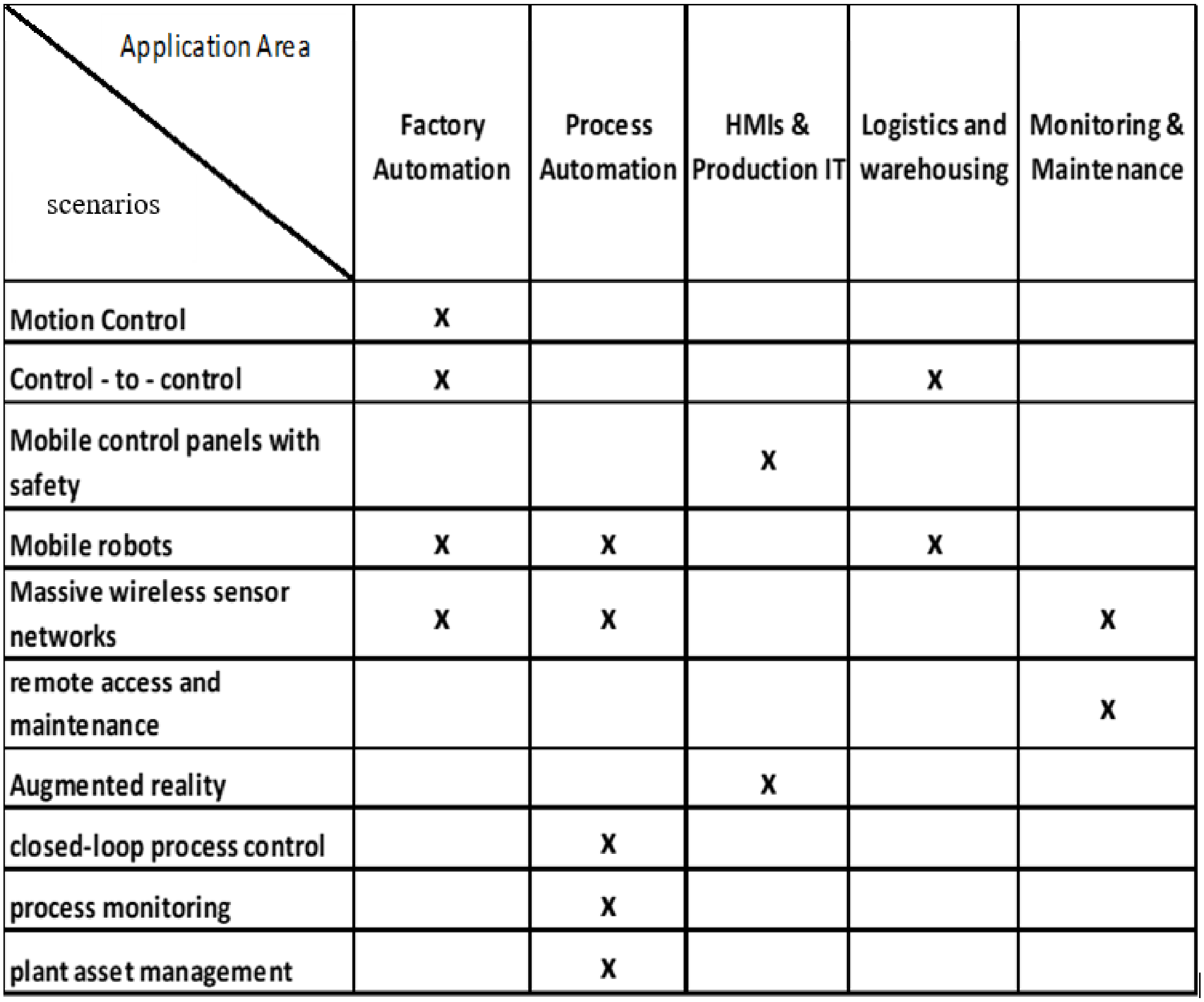
Industrial Systems	**Communication traffic category**	**Case**	**Priority**	**Applications**	**Tolerance**		**Medium Access control**
					Time constraint	**Reliability Requirements**	
Safety/Emergency systems	Safety/Emergency communication traffic	-	Very high	Emergency/Alarms Asynchronous	Few milliseconds	High reliability requirements	Pilot channels, dedicated frequency, prioritized slotted access
Close Loop Regulatory control systems	Regulatory control communication traffic	-	high	Close loop process control/critical feedback periodic	Tens of milliseconds	High reliability requirements	Slotted access using TDMA or high priority CSMA/ CA based channel access with enabled retransmissions
Close loop supervisory systems	Supervisory control communication traffic	i. Critical	high	Close loop process control/critical feedback periodic	Tens of milliseconds	High reliability requirements	Slotted access using TDMA or high priority

							CSMA/ CA based channel access with enabled retransmissions
		ii. Non-Critical	Low	Asynchronous occasional feedbacks	Seconds to hours	Low reliability with occasional packet misses	CSMA/CA based channel access
Open Loop Control systems	Open Loop Control communication traffic	-	Medium	Periodic	Seconds to minutes	Medium reliability requirements	Slotted access/(CSMA/CA) based channel access with high priority overwrite ability
Alerting systems	Alerting communication traffic	i. Critical	Medium	Periodic	Seconds to minutes	Medium reliability requirements	Slotted access/(CSMA/CA) based channel access with high priority overwrite ability
		ii. Non-Critical	Low	Asynchronous occasional feedbacks	Seconds to hours	Low reliability with occasional packet misses	CSMA/CA based channel access
Information gathering systems	Monitoring communication traffic	-	-	Monitoring application static/ feedback	Minutes to hours	Low reliability requirements	Best effort service, CSMA/CA based channel access

3.3.3 Industrial systems’ application areas and scenarios

The above data presented in Table 3.1, categorizes the types of industrial systems, and their affiliated types of communication traffic in an industrial environment, that defines the priority requirements, time deadlines, class of control systems, and relative medium access schemes. This categorization is very essential along with the categorization of different application areas and scenarios, and the different wireless standards and protocols that are available relative their attributes, in determining the most suitable industrial wireless network to use in different scenarios. Furthermore, as mentioned before, there are many types of industries available and each industry has different requirements according to their application area and scenario respectively. Thus, an identification of the industrial application areas available and their respective scenarios such as motion control, mobile robots, augmented reality etc. is essential as it produces a more specific requirements list of the scenarios under consideration which in turn, provides the user the ability of determining under which class a specific or multiple industrial systems falls from (Table 3.1). hence, increasing the accuracy of determining the level of importance for any system. Thus, presented below, is Table 3.2, that categorizes the different application areas and their scenarios accordingly:

Table 3.2 – Industrial systems' application areas and scenarios (Gangakhedkar et al. 2018):

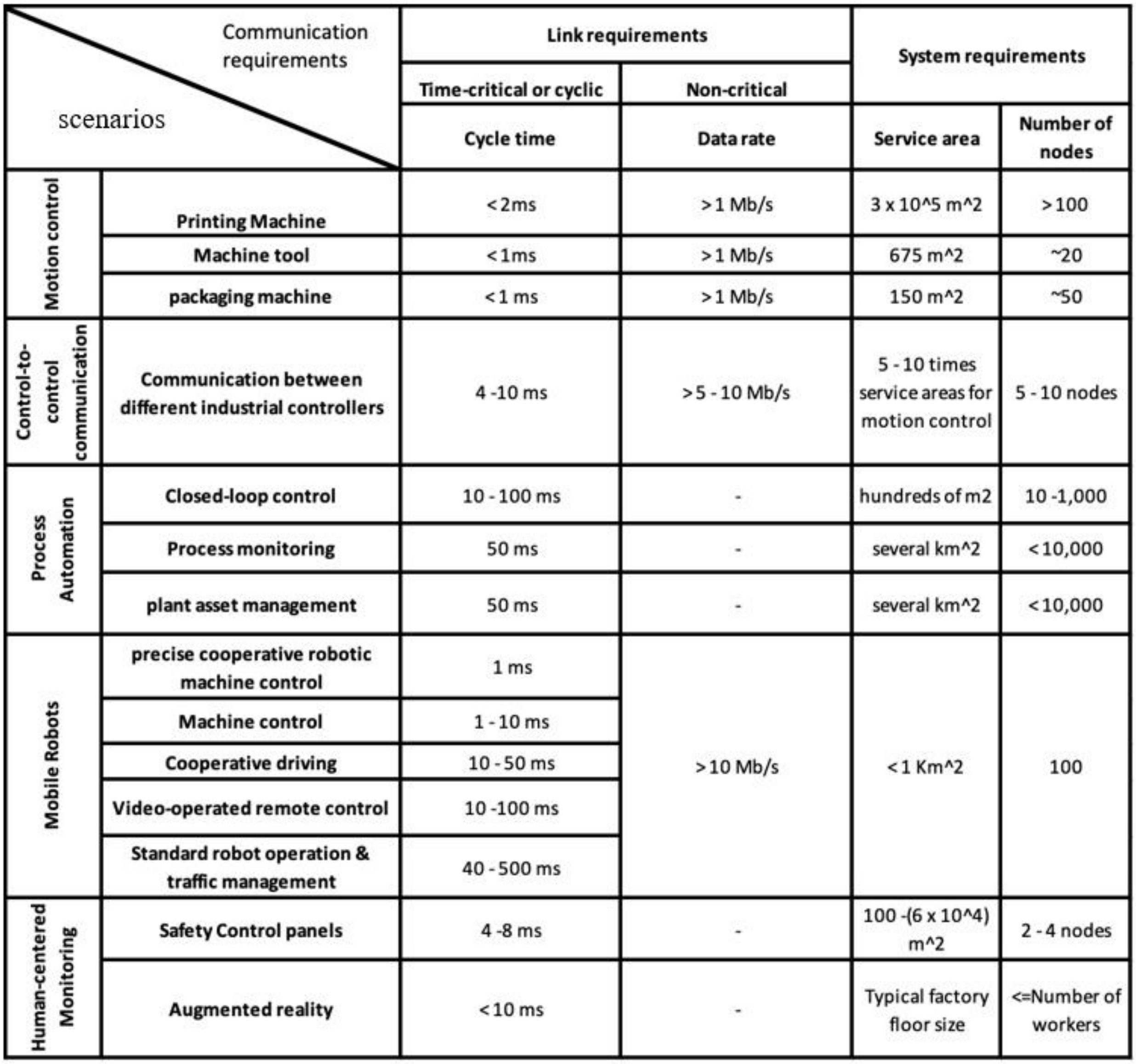


Application Area scenarios	Factory Automation	Process Automation	HMIs & Production IT	Logistics and warehousing	Monitoring & Maintenance
Motion Control	X				
Control - to - control	X			X	
Mobile control panels with safety			X		
Mobile robots	X	X		X	
Massive wireless sensor networks	X	X			X
remote access and maintenance					X
Augmented reality			X		
closed-loop process control		X			
process monitoring		X			
plant asset management		X			

3.3.4 Industrial Systems requirements

After identifying the potential application areas and scenarios in an industrial environment, a categorization of the respective communication requirements in terms of link requirements that are latency and data rate and the industrial system requirements that are the service area and the number of nodes required for an industrial system. This step provides the user with an in-depth insight of which is the most important/critical industrial system an IWSN is been selected for and accordingly reflect that in the Excel-ready AHP tool. Thus, presented below, is Table 3.3 providing the categorized list of industrial system requirements respective their application area and scenario:

Table 3.3 - Industrial system requirements (adapted from (Gangakhedkar et al. 2018)):

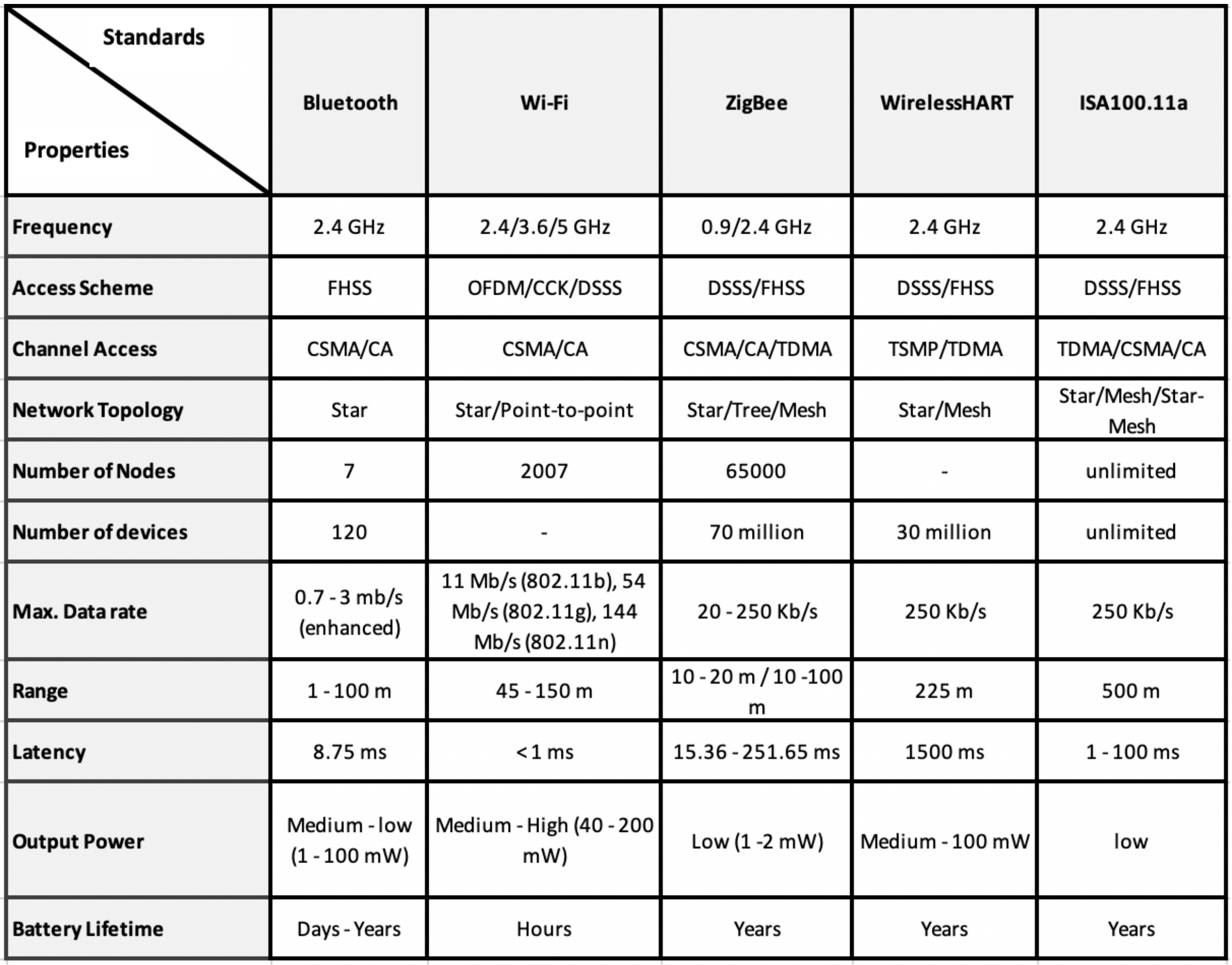


Communication requirements / scenarios		**Link requirements**		**System requirements**	
		Time-critical or cyclic	**Non-critical**		
		Cycle time	**Data rate**	**Service area**	**Number of nodes**
Motion control	**Printing Machine**	< 2ms	> 1 Mb/s	3 x 10^5 m^2	> 100
	Machine tool	< 1ms	> 1 Mb/s	675 m^2	~20
	packaging machine	< 1 ms	> 1 Mb/s	150 m^2	~50
Control-to-control communication	**Communication between different industrial controllers**	4 -10 ms	> 5 - 10 Mb/s	5 - 10 times service areas for motion control	5 - 10 nodes
Process Automation	**Closed-loop control**	10 - 100 ms	-	hundreds of m2	10 -1,000
	Process monitoring	50 ms	-	several km^2	< 10,000
	plant asset management	50 ms	-	several km^2	< 10,000
Mobile Robots	**precise cooperative robotic machine control**	1 ms	> 10 Mb/s	< 1 Km^2	100
	Machine control	1 - 10 ms			
	Cooperative driving	10 - 50 ms			
	Video-operated remote control	10 -100 ms			
	Standard robot operation & traffic management	40 - 500 ms			
Human-centered Monitoring	**Safety Control panels**	4 -8 ms	-	100 -(6 x 10^4) m^2	2 - 4 nodes
	Augmented reality	< 10 ms	-	Typical factory floor size	<=Number of workers

3.3.5 Wireless Sensor Network Technologies

In addition to identifying different industrial systems, their use applications and relative communication traffic conditions, categorizing the available wireless protocols/standards that could fulfil the requirements associated with the aforementioned is needed. However, before identifying the current wireless protocols/standards that are available to choose from, an identification of the two levels that exist in an industrial wireless system is imperative. According to (Frotzscher et al. 2014), The industrial wireless system is divided into two levels; the sensor level and the field level (local area network (LAN)). This thesis is only concerned with the sensor level because of its important role in industrial automation, the sensor level is further sub-divided into two sections, process automation and discrete factory automation. Typical application fields of wireless systems in both areas are the connection of movable machine parts or mobile machines integrated in distributed control systems (Frotzscher et al. 2014). Thus, after identifying the associated sub-divisions in the sensor level, a further specified categorization of the different wireless protocols/standards according to their automation type suitability will further aid the selection process accordingly and is presented below in Table 3.4:

Table 3.4 - Industrial Wireless Sensor Network technologies and their respective properties:



Standards / Properties	Bluetooth	Wi-Fi	ZigBee	WirelessHART	ISA100.11a
Frequency	2.4 GHz	2.4/3.6/5 GHz	0.9/2.4 GHz	2.4 GHz	2.4 GHz
Access Scheme	FHSS	OFDM/CCK/DSSS	DSSS/FHSS	DSSS/FHSS	DSSS/FHSS
Channel Access	CSMA/CA	CSMA/CA	CSMA/CA/TDMA	TSMP/TDMA	TDMA/CSMA/CA
Network Topology	Star	Star/Point-to-point	Star/Tree/Mesh	Star/Mesh	Star/Mesh/Star-Mesh
Number of Nodes	7	2007	65000	-	unlimited
Number of devices	120	-	70 million	30 million	unlimited
Max. Data rate	0.7 - 3 mb/s (enhanced)	11 Mb/s (802.11b), 54 Mb/s (802.11g), 144 Mb/s (802.11n)	20 - 250 Kb/s	250 Kb/s	250 Kb/s
Range	1 - 100 m	45 - 150 m	10 - 20 m / 10 -100 m	225 m	500 m
Latency	8.75 ms	< 1 ms	15.36 - 251.65 ms	1500 ms	1 - 100 ms
Output Power	Medium - low (1 - 100 mW)	Medium - High (40 - 200 mW)	Low (1 -2 mW)	Medium - 100 mW	low
Battery Lifetime	Days - Years	Hours	Years	Years	Years

Presented in Table 3.4 are the important criteria considered when selecting an IWSN technology. The important criteria obtained are latency, max. data rate, transmission range, and number of nodes, and their numerical properties are presented to the user randomly without mentioning which wireless technology it belongs to. Furthermore, the user inputs their relative importance to one another for each criterion accordingly, and thus, is provided with a total weight factor based on the calculations made in AHP for each option. Thus, a clear vision is now formed with the identification of the different system types, their relative communication traffic types and properties, industrial application areas and their respective scenarios and their requirements, and finally the available wireless technologies and their respective properties. Next, Analytic

Hierarchy Process (AHP) decision support tool is used to select a suitable Industrial Wireless Sensor Network technology accordingly.

3.3.6 Analytic Hierarchy Process (AHP) Tool Development

The developed excel sheet that utilizes Analytic Hierarchy Process techniques is used to provide an IWSN technology recommendation to the user through comparing and measuring the relative importance of the industrial communication requirements of industrial equipment present in an industrial environment providing each with a weighting factor based on the relative importance inputted by the user. Next, a total percentage weight is calculated for each requirement present in the different industrial system under evaluation. Next, the available Industrial Wireless Sensor Network technologies' options within each criterion of the communication requirements are evaluated in the same concept relative their importance according to the known industrial system's communication requirements. Finally, the alternative options of IWSN technologies available are given a total benefit score according to their properties' total percentage score from each of the four criterions considered (cycle time, data rate, range, and number of nodes). The user is then provided an overall benefit score for each IWSN technology alternative in a ranking form with the highest percentage score being the best beneficial option to fit the user's industrial requirements and the lowest percentage weight score for the least beneficial IWSN technology alternative. In addition, a prioritization protocol is provided to the user to be followed in the case where the outcome yielded identical beneficial scores for two or more IWSN technology alternatives.

A detailed illustration is provided in the case study presented in chapter 4 of this thesis.

Below are the equations used in the developed excel sheet ready AHP tool:

1) Magnitude of importance (MOI): A score of 1-9 inputted by the user (Rangone 1996) (1)

- Equally preferred - 1
- Moderately preferred - 3
- Strongly preferred - 5
- Very strongly preferred - 7
- Extremely preferred - 9

2) MOI ratio (relative importance) = $(\text{MOI})_a / (\text{MOI})_b$ (2)

a and b are used to distinguish between two industrial equipment (CNC machine, Robot, etc.), criteria (cycle time, data rate, etc.), or criteria options' available within each criterion.

3) $(\text{Weight Percentage})_{\text{cell(i)}} = [(\text{MOI ratio})_{\text{cell(i)}} / \sum (\text{MOI ratio})_{\text{col(i)}}]$ (3)

Col and row refer to the columns and rows where different MOI ratios for Industrial equipment, criteria, or criteria options available within each criterion are calculated in the developed AHP tool as shown in Table 4.8,

cell represents the cell of the calculated MOI ratio value for each, two Industrial Equipment, criteria, or options available within each criterion in the Table and column is the column of that cell.

4) $(\text{Average weighted percentage})_{\text{row(i)}} = \sum(\text{weight percentage})_{\text{row(i)}} / N$ (4)

N: number of weighted percentage cells in a $\text{row}_{\text{(i)}}$

5) Percentage score = $(\text{Average Weight Percentage})_{\text{row(i)}} \times 100$ (5)

6) relative percentage importance score =

$(\text{percentage score})_x \times (\text{weight percentage})_z$. (6)

X represents the percentage importance score of either a criterion or an option available within a criterion compared to other criterions/options relatively.

Z represents the weighted percentage of either the industrial equipment that a criterion's percentage importance score will be related to, or of a criterion that an available option's percentage importance score within that criterion will be related to.

7) IWSN technology option benefit score = $\sum$ IWSN technology options' percentage scores (7)

Numerical illustration of the use of the AHP method is included in chapter 4.

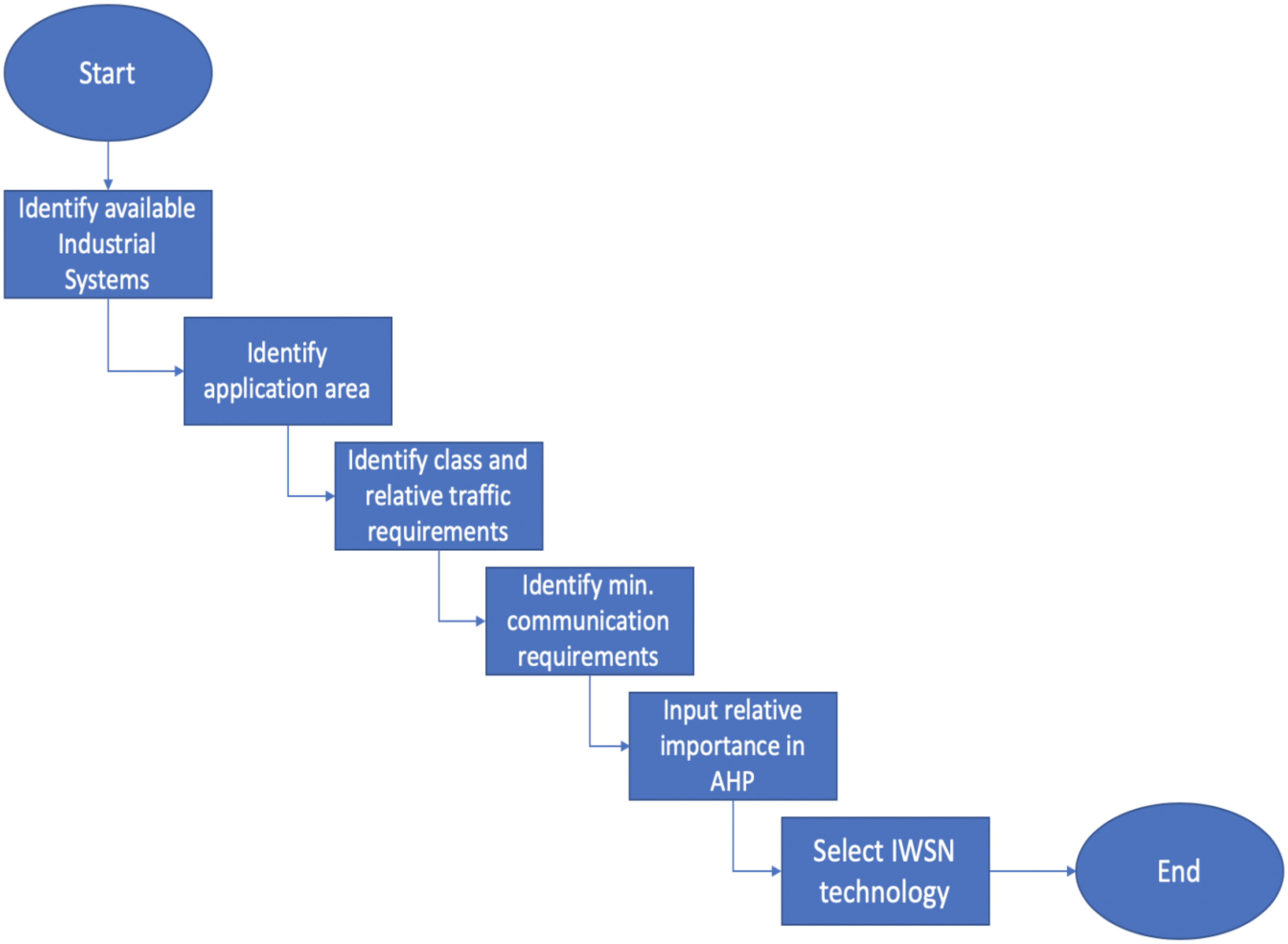


Figure 3.3 - IWSN selection process Flowchart

3.4 Conclusion

In this chapter, the IWSN technology selection process was introduced, the main difference compared to other researchers' work is that actual data from industrial systems' requirements are considered relevant their application area and criticality beforehand. In addition, the state of art IWSNs are considered along with a clear identification of their properties that are applicable to different industrial automation processes unlike in previous researches, where such information was either lacking or incomplete. The aforementioned identifications/considerations are beneficial in enhancing the selection process because of their detailed level of analyzing what IWSN communication requirements are expected/required for the industrial system; thus, enhancing the effectiveness of the overall system's communication performance. Furthermore, an excel-sheet-ready Analytic Hierarchy Process (AHP) decision-support tool is developed to be used with the information presented in Tables (3.1-3.4) to obtain a recommended suitable IWSN technology for one or more industrial systems. Moreover, such tool was not found in previous researches; however, other methods of comparisons and IWSN recommendations were found such as a performance evaluation using a small lab that does not reflect the real-life industrial case scenarios but rather provides a slight insight of how a specific IWSN technology could perform. In addition, these methods lack accuracy and precision due to the absent factory components such as ones that produce strong vibrations that could interfere with the IWSN transmitted signals, disrupting their cause. Thus, taking into consideration the industrial systems' communication requirements, their class, communication traffic types, and the IWSNs properties, along with the utilization of developed AHP excel sheet ready tool, provides a more accurate, precise, and a suitable IWSN technology recommendation.

In chapter 4, an industrial case study in collaboration with SPM Automation Inc. is used to present the mathematical calculations AHP uses to select/recommend a suitable IWSN technology option.

CHAPTER 4

INDUSTRIAL WIRELESS SENSOR NETWORK SELECTION METHODOLOGY

This chapter will illustrate the 6-step IWSN technology selection process presented in chapter 3 using a case study carried out at SPM Automation Inc.

4.1 SPM Automation Inc. Case Study

A case study performed in collaboration with SPM Automation Inc. in Windsor, Ontario is arranged. SPM Automation is considered a small / medium enterprise (SME) aiming to provide automatic solutions for various challenges such as, plastics joining, assembling, and finishing applications. Automotive part suppliers such as FlexNGate, AP Plasman, and Magna are some of their common clients. Moreover, their engineering mission is focused on designing and building different types of plastic welding machines used to manufacture various automotive parts that include but are not limited to interior and exterior vehicle components, fuel tanks, taillights, and assemblies. SPM Automation Inc. is a manufacturing company that consists of industrial systems from different industrial classes with different application areas, and communication requirements. In addition, SPM Automation Inc. has proven to be connected to academic institutes such as the University of Windsor since they provide visits for students to their facilities and share their knowledge and experiences with students by providing guest speakers and allowing their facilities to participate in case studies concerning recent research. Thus, they agreed to provide us with the great opportunity to conduct this case study using their facility. In addition, it is important to mention that SPM Automation Inc. currently uses wired connectivity settings at their company; however, a shift in the connectivity settings from wired to wireless is inevitable to comply with

I4.0's technical advances. Therefore, this case study aims to gather all the information provided by the management and staff at SPM Automation Inc. to provide a clear understanding of the challenge at hand, the research scope and the expected outcome of the research, such that in the future, if SPM Automation Inc. decides to expand their production and shift their communication technologies from being wired to wireless, this thesis research may be used to implement such changes. Thus, all the information presented in this section regarding the CNC machines, robot track added and their shift to wireless technology does not represent their current vision. A top view layout presented in Figure 4.1 is used to demonstrate the different industrial equipment' settings at SPM Automation Inc.

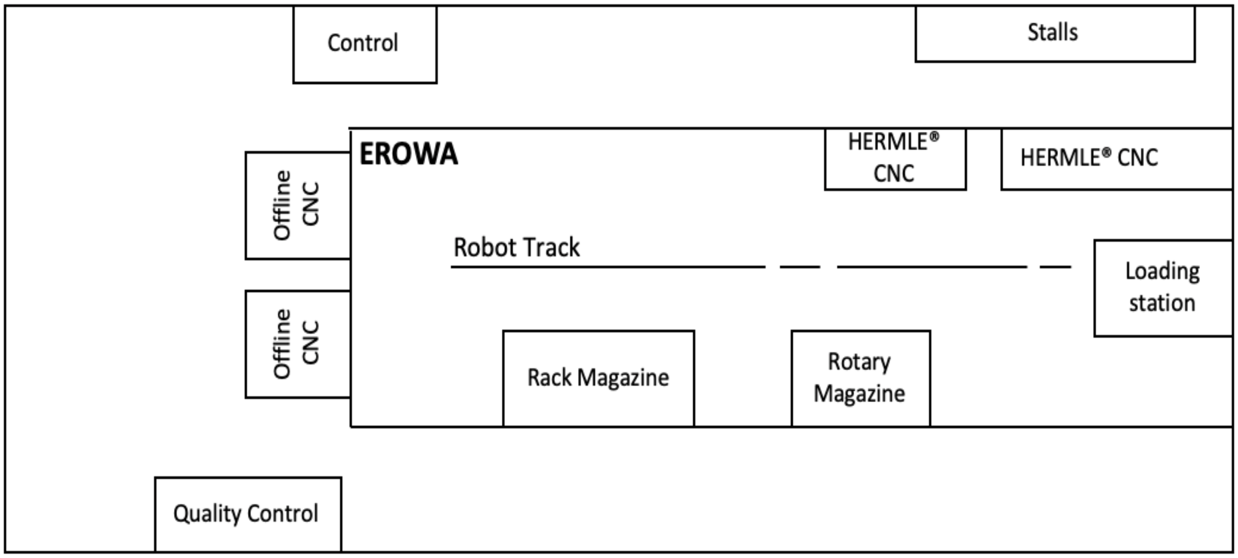


Figure 4.1 - SPM Automation Inc. Facility Floor Plan and the EROWA® automated manufacturing system

4.2 Selecting an IWSN technology process

The selection of an IWSN technology process was initiated with a visit to SPM Automation Inc. facilities with the aim to achieve the following: 1) a visual of the SPM Automation Inc.'s facility floor plan layout shown in Figure 4.1, 2) the work processes that the enterprise practices, 3) the machines and tools used, and finally, 4) their expanding vision that includes what processes, machines, etc. they are considering to add. Thus, SPM Automation Inc.'s work process and organizational structure is as follows: The automotive supplier (client) provides SPM with a detailed description (CAD drawings and parameters) of the part(s) required to be manufactured, which in turn are submitted to the engineering department whose job is to plan and design the machine's components. Next, the raw materials are supplied to the shop floor for operators to initiate the manufacturing process. The work process and the organizational structure consists of industrial systems, that are limited to CNC machining, Welding, controls design, software programming, assembly, and machine testing.

Below are photos of the machines/equipment by EROWA® currently used at SPM Automation Inc. (used with permission from SPM Automation).

Figure 4.2 - EROWA® from outside

Figure 4.3 - EROWA® from inside

Figure 4.4 - EROWA® rack magazine

Figure 4.5 - SPM Automation Inc. operator loading EROWA® rotary magazine

Figure 4.6 - SPM Automation Inc. operator placing raw material in CNC machine

Figure 4.7 - EROWA® round fixtures

Figure 4.8 – A HERMLE® CNC machine during operation

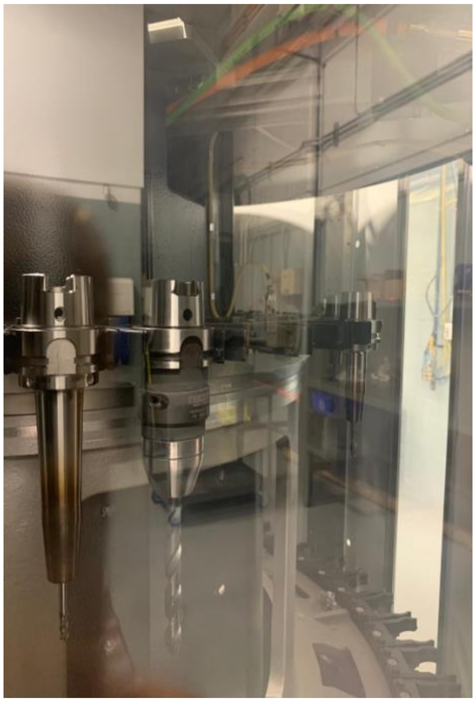


Figure 4.9 - EROWA® tool magazine

SPM Automation Inc.’s top view facility floor plan shown in Fig 4.1 shows that their shop floor area of 16,000 ft^2 (1486 m^2) is mostly occupied by EROWA®. SPM Automation Inc. aims to acquire/utilize recent technology advancements to ensure their manufacturing machines are flexible, scalable, and reconfigurable, which is why they implemented EROWA®’s system solutions. EROWA® specializes in providing system solutions that ensures an improved machine workflow and a minimized downtime, through building flexible systems that easily automates the production of individual parts. EROWA®’s multi-cellular capabilities consist of a rack magazine shown in Figure 4.4 that loads the round fixtures displayed in Figure 4.7 and a rotary magazine shown in Fig 4.5 which loads those round fixtures. Also, included in EROWA®’s multi-cells, are two HERMLE® CNC machines and a loading station. Furthermore, to gain a clearer insight of how EROWA® operates, a part’s operation scenario was witnessed with the thorough information guidance of one of SPM Automation Inc.'s operators. First, the operator loads the rack with the raw material either being fixtured on a spherical fixture if it is small in size, or on a rectangular fixture if otherwise. Secondly, a robot moving on the track shown in Figure 4.1 takes the fixtures and places them in one of the assigned CNC machine stations. The CNC machines receive instructions to perform different manufacturing processes such as milling, drilling, etc. Variable manufacturing process instructions that are dependent on the product variant are inputted into each machine. Lastly, after the CNC machine successfully completes all the manufacturing processes required, the robot picks the part again and places it on the rack magazine shown in Figure 4.4. No human intervention is involved/required in this process. Furthermore, other processes such as welding, assembling and packaging of the parts that create the machine solutions provided by SPM Automation Inc., etc. are done manually.

Furthermore, due to SPM Automation Inc.'s nature of business which requires frequent changes in customer demand, human intervention/integration/interaction remains an essential requirement and could never be eliminated and thus, maintaining their manual stations where operations such as, welding, assembling, and machine testing takes place without further automating them is considered an asset.

However, this case study considers a future scenario if they decide to expand their production line due to an increase in the workload/customers demand. SPM Automation Inc. could add two more HERMLE® CNC machines, one offline CNC machine, and extend the track for the existing moving robot to accommodate this increase. As a result, this research would be beneficial if SPM Automation Inc. decides to shift their connectivity settings into wireless connectivity, to further benefit from the technical advances associated with the shift towards I4.0 such as increased flexibility, enhanced connectivity, reduction in cable costs, as well as improved scalability and reconfigurability of their industrial system, adding/removing more/less machines when needed and as needed (ElMaraghy et al. 2013).

Due to the multiple IWSN technology options present, selecting the most suitable option that fits their industrial needs is not an easy task. This highlights the motivation of this thesis to solve this problem.

A layout of the shop floor was provided by the enterprise (Figure 4.1), as well as an industrial equipment list where the machines and their relevant quantities currently present and considered for the future are shown.

Thus, presented below in Table 4.1, are the equipment list and their relative quantities, currently and after the potential additions:

Table 4.1 – SPM Automation Inc.'s current and planned Industrial equipment:

Industrial equipment	**Quantity (Current)**	**Quantity (after)**
CNC Machine (HERMLE®)	**2**	**4**
Offline CNC machine	**2**	**3**
Moving robot (EROWA®)	**1**	**1**

In addition, Fig 4.10 below shows the potential SPM Automation Inc. floor plan layout:

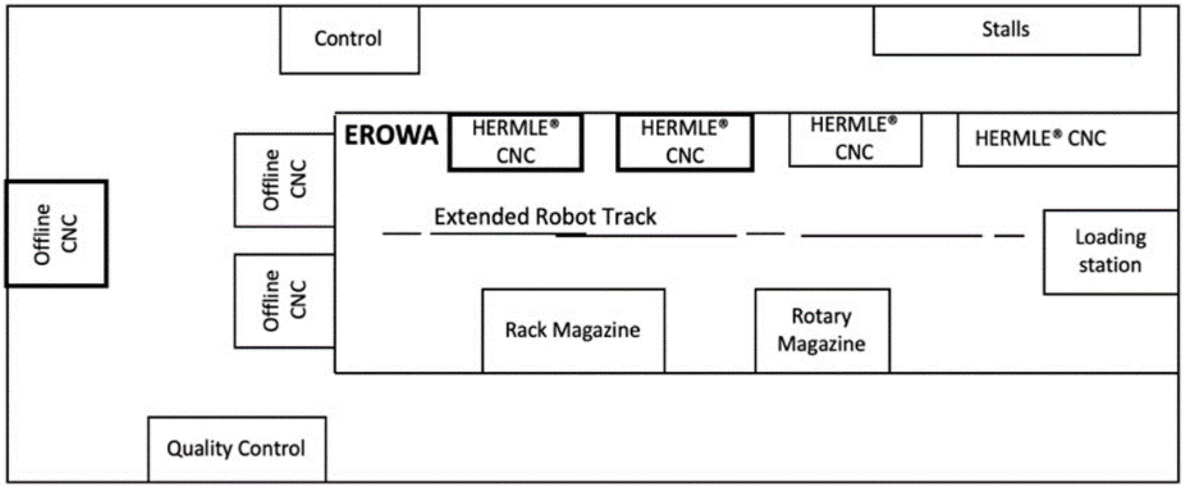


Figure 4.10 - SPM Automation Inc.'s facility layout floor plan with the proposed equipment additions

4.2.1 Identifying the class and criticality of the industrial system

Using table 3.1, the industrial equipment presented in table 4.1 are categorized under the close loop regulatory control industrial system class as shown in table 4.2 below. Both CNC machines online (HERMLE®) and offline, and the moving robot (EROWA®), are categorized as a closed loop control system class types; since they provide feedback to verify sensed parameters, and due to the criticality of the manufacturing processes at SPM Automation Inc.

Thus, communication traffic types for each of the manufacturing systems are determined using table 3.1 and is presented below in Table 4.2:

Table 4.2 - Industrial system's class and communication traffic type (adapted from (Raza et al. 2017)):

Industrial Systems	**Communication traffic category**	**Case**	**Priority**	**Applications**	**Tolerance**		**Medium Access control**
					Time constraint	**Reliability Requirements**	
Close Loop Regulatory control systems	Regulatory control communication traffic	-	high	Close loop process control/critical feedback periodic	Tens of milliseconds	High reliability requirements	Slotted access using TDMA or high priority CSMA/ CA based channel access with enabled retransmissions

Therefore, from the table above (Table 4.2), high criticality and reliability requirements have been determined.

4.2.2 Identifying the application area(s) of the identified industrial systems

Further to identifying the industrial equipment's class and communication traffic type, an application area identification is the next the step. From Table 3.5, the CNC machines, both online (HERMLE®) and offline, are categorized as motion control systems under factory automation. As for the moving robot (EROWA®), it is categorized as a mobile robot under both factory and process automation but in this case is considered to be under factory automation as shown in table 4.3 below:

Table 4.3 - Industrial equipment's application area and scenarios (adapted from (Gangakhedkar et al. 2018)):

Application Area Scenarios	**Factory Automation**	**Process Automation**	**HMIs & Production IT**	**Logistics and warehousing**	**Monitoring & Maintenance**
Motion Control	x				
Control - to - control	x			x	
Mobile control panels with safety			x		
Mobile robots	x	x		x	

Thus, after determining the industrial equipment's application area, the next step is to determine the communication requirements associated to them.

4.2.3 Identifying the industrial systems' communication requirements

From table 4.2, we identified the industrial equipment's class and communication traffic type. Furthermore, an identification of the industrial equipment's application area and scenario to determine the industrial equipment's categorization shown in Table 4.3 was also obtained. This provides the user with the respective communication requirements of the industrial systems at hand. Thus, using the information obtained from Tables 4.2 and 4.3, with the consideration of the criticality of the communication traffic types, Table 3.3 is used to obtain the communication requirements accordingly. Therefore, because of the proportional relationship between an industrial system's priority and criticality, if an industrial system is highly prioritized, then their criticality of communicating data is high as well; therefore, data communication needs to be done in time and cannot afford delays or blockages (errors). Hence, presented below in Table 4.4, are the industrial equipment's communication requirements.

Table 4.4 - Industrial equipment's communication requirements (adapted from (Gangakhedkar et al. 2018):

Communication requirements / Scenarios		**Link requirements**		**System requirements**	
		Time-critical or cyclic	**Non-critical**		
		Cycle time	**Data rate**	**Service area**	**Number of nodes**
Motion Control	**Machine tool**	<= 1 ms	> 1 Mb/s	675 m^2	~20
Mobile Robots	**Standard robot operation & communication traffic management**	40 - 500 ms	> 10 Mb/s	< 1 Km^2	~100

Thus, from table 4.4, the communication requirements for the manufacturing industrial equipment are identified. However, since there are different quantities associated with each Industrial equipment, new calculated number of nodes and a minimum service area's range requirement are considered. The new calculated requirements are helpful when using the AHP calculator for the Industrial wireless sensor networks decision making process and is presented in table 4.5 below:

Table 4.5 - Modified Industrial Systems' communication requirements:

Industrial System	**Number of nodes**	**Service Area**
CNC Machines (HERMLE®)	20 nodes x 4 = 80 nodes	SPM Automation Shop floor size
Offline CNC machines	20 nodes x 3 = 60 nodes	
Moving robot (EROWA®)	100 nodes x 2 = 200 nodes	
Total	**240 nodes**	**1486 m2**

Thus, with the new calculated requirements, it is determined that the IWSN technology option needs to accommodate the installation of approximately 240 nodes and provide a service area range of 1486 m_2. With these obtained requirements, the process of selecting/recommending a suitable IWSN technology option using the excel sheet ready AHP calculator is initiated.

4.2.4 Using AHP calculator to select a suitable IWSN

With the successful identification of the industrial equipment, their industrial class and communication traffic types to determine their data communication priority and reliability, their matching application area and scenario, and finally their relevant communication requirements, the last step is to use the developed Excel sheet ready AHP calculator to determine a suitable IWSN technology that fits the obtained requirements.

To use AHP, the industrial equipment communication requirements obtained should be taken into consideration to feed their relative importance to one another accordingly as shown in Table 4.6 below. The inputted magnitudes of importance are thus subjective to the industrial equipment an IWSN technology is been determined for. Therefore, the magnitude of importance changes accordingly with different communication requirements obtained from Tables 3.1, 3.2, and 3.3 for different industrial equipment.

Table 4.6 - Relative importance of each industrial equipment to one another:

Industrial Equipment	**Magnitude of importance**
CNC Machines (HERMLE®)	**9**
Offline CNC machines	**5**
Moving robot (EROWA®)	**7**

After inputting the importance of each industrial equipment, AHP divides the magnitude of importance of each industrial equipment to one another to obtain their relative importance to each other (red circle) using equation (1) as shown in (Table 4.7) from the excel sheet ready AHP calculator. Next, AHP calculates the total relative importance ratio (yellow circle) of each industrial equipment by adding their vertical relative importance ratio values calculated using equation (2) as shown in Table 4.8. AHP then calculates the weighted percentages of each industrial equipment (blue circle) in Table 4.8 by dividing each individual relative importance (red circle) of each industrial equipment by its calculated relative importance total (yellow circle) using equation (3). Finally, AHP calculates a final percentage total (purple circle) that add up to 100% for each industrial equipment according to their relative importance inputted, by calculating the average relative percentage weight of each industrial equipment's row in Table 4.8 using equation (4) and multiplying it by 100 using equation (5) as shown in Table 4.9.

Presented below is a sample the aforementioned AHP calculations, numerically illustrated:

1) Relative magnitude of importance of offline CNC machines to CNC machines (HERMLE®):

5/9 = 0.56

2) vertical relative importance total of CNC machines (HERMLE): 1 + 0.56 + 0.78 = 2.33

3) Relative vertical weighted percentage total of CNC machines (HERMLE®):

1 / 2.33 = 0.43

0.56 / 2.33 = 0.24

0.78 / 2.33 = 0.33

4) Overall relative percentage total of CNC machines (HERMLE®):

((0.43 + 0.43 + 0.43) / 3) x 100 = 43%

Table 4.7 - AHP calculation process part 1:

Industrial Equipment	CNC Machines (HERMLE®)	Offline CNC machines	Moving robot (EROWA®)
CNC Machines (HERMLE®)	1	**1.8**	**1.29**
Offline CNC machines Reciprocal	0.56	1	**0.71**
Moving robot (EROWA®)	0.78	1.4	Reciprocal 1
Total	**2.33**	**4.2**	**3**

Table 4.8 - AHP calculation process part 2:

Industrial Equipment	CNC Machines (HERMLE®)	Offline CNC machines	Moving robot (EROWA®)
CNC Machines (HERMLE®)	1	**1.8**	**1.29**
Offline CNC machines	**0.56**	1	**0.71**
Moving robot (EROWA®)	**0.78**	**1.4**	1
Total	**2.33**	**4.2**	**3**
Industrial Equipment	CNC Machines (HERMLE®)	Offline CNC machines	Moving robot (EROWA®)
CNC Machines (HERMLE®)	0.43	0.43	0.43
Offline CNC machines	0.24	0.24	0.24
Moving robot (EROWA®)	0.33	0.33	0.33

Table 4.9 - AHP calculations process part 3:

Industrial Equipment	weight (%)
CNC Machines (HERMLE®)	42.86
Offline CNC machines	23.81
Moving robot (EROWA®)	33.33

After inputting the relative importance for each industrial system according to the industrial systems' class and communication traffic types. The next step is to input the magnitude of importance of each criterion of the communication requirements. The user would then input an importance score out of 9 as mentioned in section (3.3.6) for each communication criterion: i) cycle time, ii) data rate, iii) service area, and iv) number of nodes based on the data read from Table 4.4. This will determine a total overall percentage score for each criterion but at this stage it would not be associated to any industrial equipment. The overall percentage scores for each criterion are then multiplied with the overall percentage score of their relative industrial equipment to obtain the reflected magnitude of importance of that specific criterion as a percentage of its relative industrial equipment and relative the entire industrial system using equation (6).

An example of this calculation for the CNC machine (HERMLE®) is demonstrated in Tables 4.10, 4.11, and 4.12 below for further illustration.

Table 4.10 - AHP calculations process part 4:

CNC Machines (HERMLE®)	**Insert the magnitude of importance**
cycle time	**9**
Data rate	**7**
Service Area	**4**
Number Nodes	**3**

Table 4.11 Table 4.11 - AHP calculations process part 5:

CNC Machines (HERMLE®)	cycle time	Data rate	Service Area	Number Nodes
cycle time	1	**1.29**	**2.25**	**3**
Data rate	0.78	1	**1.75**	**2.33**
Service Area	0.44	0.57	1	**1.33**
Number Nodes	0.33	0.43	0.75	1
Total	**2.56**	**3.29**	**5.75**	**7.67**
CNC Machines (HERMLE®)	cycle time	Data rate	Service Area	Number Nodes
cycle time	0.39	0.39	0.39	0.39
Data rate	0.30	0.30	0.30	0.30
Service Area	0.17	0.17	0.17	0.17
Number Nodes	0.13	0.13	0.13	0.13

Reciprocal

Table 4.12 - AHP calculations process part 6:

CNC Machines (HERMLE®)	**weight value (%)**
cycle time	**39**
Data rate	**30**
Service Area	**17**
Number Nodes	**13**

Thus, AHP calculation processes done in tables 4.10, 4.11, and 4.12 for machine tool, is repeated for the packaging machine, and the welding robot. Hence, the total weighted percentage score for each of the aforementioned industrial systems are shown below in table 4.13.

Table 4.13 - AHP calculations process part 7:

Industrial System	**criterion**	**weight %**
CNC Machines (HERMLE®)		
	cycle time	**14**
	Data rate	**11**
	Service Area	**8**
	Number Nodes	**10**
Offline CNC machines		
	cycle time	**10**
	Data rate	**6**
	Service Area	**3**
	Number Nodes	**5**
Moving Robot (EROWA®)		
	cycle time	**10**
	Data rate	**8**
	Service Area	**9**
	Number Nodes	**6**

After calculating a total percentage score for each criterion relative the industrial equipment its associated with, an overall total percentage score for similar criterions in all the industrial equipment is calculated by adding the percentage scores of similar criterions in each industrial equipment, for example, cycle time percentage score values (blue circle) in Table 4.13 from the online (HERMLE®) and offline CNC machines and from the moving robot are added together to produce a total importance percentage score of 34 (green circle) for cycle time as shown below in Table 4.14. This calculation is essential for multiple reasons; firstly, the end result where an IWSN technology is to be recommended is based on the total importance of each of the four criterions (cycle time, data rate, service area, and number of nodes) including all industrial equipment as a relative percentage of a total 100%. Secondly, due to the different case scenarios that could occur such as industrial equipment being added/removed, different magnitudes of importance scores inputted, such calculation ensures consistency in all evaluations to be conducted as a relative percentage out of a total of 100%. Lastly, a total percentage score for each of the different options available within each criterion is calculated as a percentage of the total percentage score for each criterion using equation (7) as shown in Table 4.14.

Table 4.14 - AHP calculations process part 8:

Criterion	**Total weight value(%)**
cycle time	**34**
Data rate	**25**
Service Area	**20**
Number Nodes	**21**

The next step after getting a total weighted percentage score for each communication requirement criterion reflecting their importance, is to obtain a weighted percentage for each option available within each criterion. There are five different IWSN technology options available. Each option contains different criteria (Medium Access scheme, Power consumption, battery lifetime, topology, cycle time, data rate, range, and number of nodes, etc.) that assists the user through IWSN technology selection and the design process after. In the case of selecting an IWSN technology, only four of the criterions presented in Table 3.4 are used, namely, latency/cycle time, number of nodes, range, and data rate, as they are the most influential out of all criterions when selecting an IWSN technology. For each criterion there are 3-5 options available with each IWSN technology. Thus, the user is presented with the available options in the excel sheet ready AHP calculator to input an importance score from 1-9 (1 being least important and 9 being the most important) for each option according to the communication requirements presented in Tables 4.2 and 4.4 as shown below in table 4.15.

Table 4.15 - AHP process calculations part 9:

Latency/cycle time options (ms)	Magnitude of importance
8.75 ms	**5**
<= 1 ms	**9**
15 ms	**3**
1500 ms	**2**
1 ms	**6**

After inputting the magnitude of importance for each option, AHP calculator will perform the same calculation process presented in Tables 4.7 to 4.11, as shown below in Tables 4.16 and 4.17.

Table 4.16 - AHP calculations process part 10:

cycle time	8.75 ms	<= 1 ms	15 ms	1500 ms	1 ms
8.75 ms	1	**0.56**	**1.67**	**2.5**	**0.83**
<= 1 ms	1.8	1	**3**	**4.5**	**1.5**
15 ms	0.6	0.33	1	**1.5**	**0.5**
1500 ms	0.4	0.22	0.67	1	**0.33**
1 ms	1.2	0.67	2	3	1
Total	**5**	**2.78**	**8.33**	**12.5**	**4.17**
cycle time	8.75 ms	<= 1 ms	15 ms	1500 ms	1 ms
8.75 ms	0.20	0.20	0.20	0.2	0.2
<= 1 ms	0.36	0.36	0.36	0.36	0.36
15 ms	0.12	0.12	0.12	0.12	0.12
1500 ms	0.08	0.08	0.08	0.08	0.08
1 ms	0.24	0.24	0.24	0.24	0.24

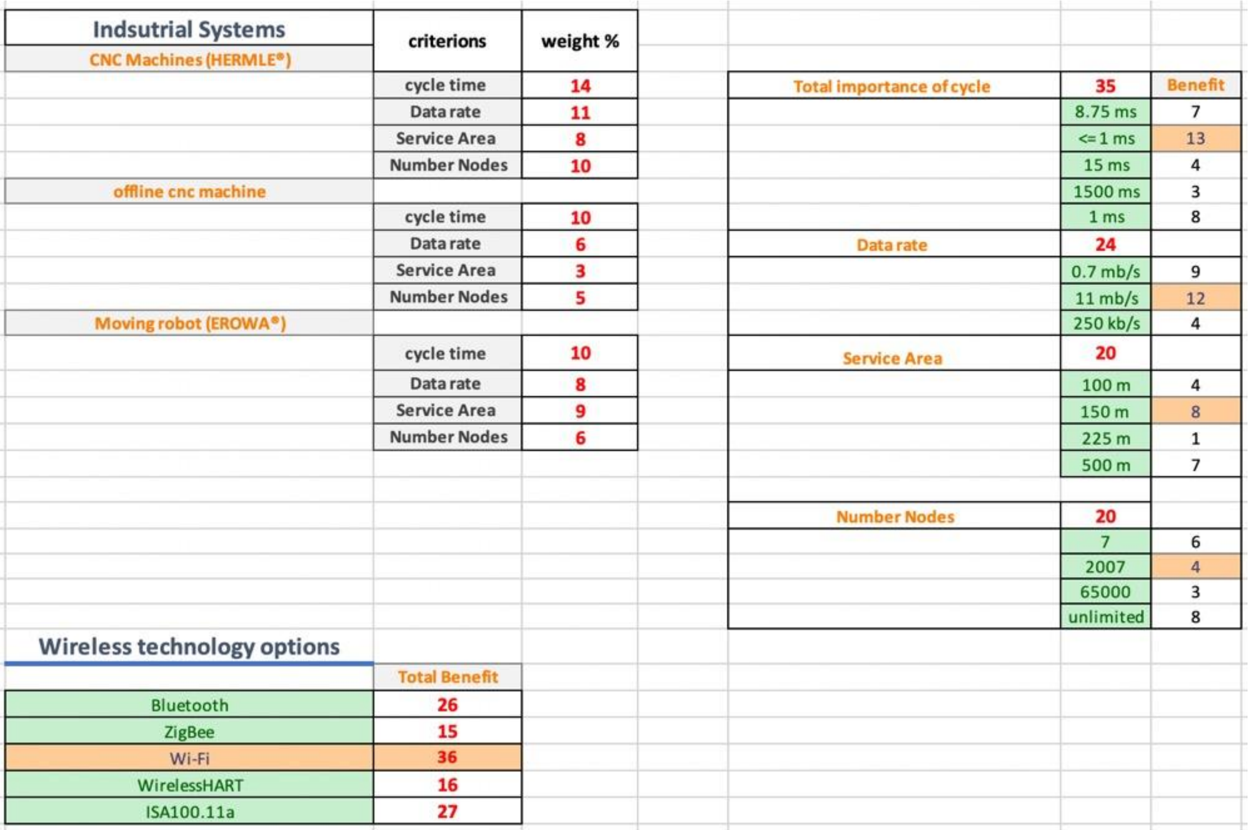
Table 4.17 - AHP calculations process part 11:

Latency/cycle time options (ms)	**Weight %**
8.75 ms	**20.00**
<= 1 ms	**36.00**
15 ms	**12.00**
1500 ms	**8.00**
1 ms	**24.00**

After a total percentage score for each option within each criterion is calculated, a total benefit percentage score is provided for each IWSN technology ranking them with the most beneficial/suitable having the highest weighted percentage score and the least beneficial/suitable having the lowest weighted percentage score. The total benefit percentage score of each IWSN Technology is based on the accumulative percentage scores of its respective options' scores within each criterion namely, cycle time, data rate, range, and number of nodes.

Presented below in table 4.18, is the final result from the excel sheet ready AHP calculator for this case study.

Table 4.18 - AHP calculations final result:



Indsutrial Systems	criterions	weight %
CNC Machines (HERMLE®)		
	cycle time	14
	Data rate	11
	Service Area	8
	Number Nodes	10
offline cnc machine		
	cycle time	10
	Data rate	6
	Service Area	3
	Number Nodes	5
Moving robot (EROWA®)		
	cycle time	10
	Data rate	8
	Service Area	9
	Number Nodes	6

Total importance of cycle	35	Benefit
	8.75 ms	7
	<=1 ms	13
	15 ms	4
	1500 ms	3
	1 ms	8
Data rate	24	
	0.7 mb/s	9
	11 mb/s	12
	250 kb/s	4
Service Area	20	
	100 m	4
	150 m	8
	225 m	1
	500 m	7
Number Nodes	20	
	7	6
	2007	4
	65000	3
	unlimited	8

Wireless technology options	Total Benefit
Bluetooth	26
ZigBee	15
Wi-Fi	36
WirelessHART	16
ISA100.11a	27

4.2.5 Road Map Construction

An IWSN technology option selection is based on multiple factors which when evaluated with respect to importance, produces an overall percentage score indicate a recommended IWSN technology option. However, it is not always the case for the excel sheet ready AHP calculator to produce an outcome where only one IWSN technology option scores the highest among the rest of the available options. Therefore, a prioritizing protocol essential to further guide the user into the appropriate IWSN technology selection when more than one option have the same highest rate. Thus, the prioritizing protocol is presented in Table 4.19 as follows:

Table 4.19 - Prioritizing protocol:

Benefit score scenarios	Prioritizing action
Different weights	Highest weight value
Identical weights	Follow selection strategy presented in Table 4.20

4.2.5.1 Identical final IWSN technology scores selection strategy

In the case where two or more IWSN technology options have identical weight scores, there are other factors that should make the difference and lead the user to the appropriate selection. Those factors include cost, topology, Medium Access Control (MAC) protocol supported, Frequency hopping strategy, and the priorities regarding the Industrial system’s communication requirements. Thus, the user would use the table displayed below (Table 4.20) as a check mark table to further assist the user in the IWSN technology selection process:

Table 4.20 - Identical benefit scores elimination strategy:

Factors	Action
1. Medium access control	Check the recommended medium access scheme in Table 3.1
2. Medium Access scheme	Based on the results obtained from Table 3.1, and with the definitions/functionalities provided for each access scheme, Table 3.4 should be used to determine the access schemes suitability between the recommended IWSN technology options.
3. Network topology	Using the definitions provided in the literature review, a suitable network topology could be determined; and thus, a suitable IWSN technology option.
4. Cost: i) Output power ii) Battery lifetime (maintenance cost)	i) Output powers associated with each IWSN technology, affect the overall energy cost. ii) Battery lifetime expectancy in different IWSN devices affects the overall maintenance cost accordingly.

Thus, since the final result of the calculations made in the excel sheet ready AHP calculator, shows that for this case study Wi-Fi would be the most suitable IWSN technology, and identical IWSN technology option scores is not the case, Wi-Fi is the recommended IWSN technology option.

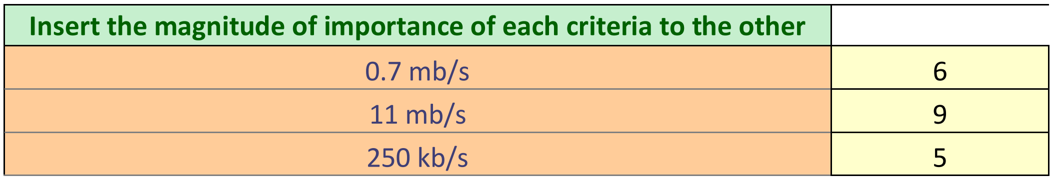
4.2.6 Verification of selected IWSN technology

After a suitable IWSN technology is selected, which in this case is Wi-Fi, a verification of the tool functionality is performed. To verify that a suitable selection is recommended, Tables 4.4 and 3.4 are used. In Table 4.4, the minimum communication requirements for cycle time was <=1 ms for both the online (HERMLE®) and offline CNC machines, a recommended data rate requirement of 10 Mb/s for the moving robot (EROWA®), a recommended minimum number of nodes of 240, and a minimum service area range of 1486 m^2 for all industrial equipment. Thus, analyzing the communication properties that Wi-Fi can provide, we can conclude that it meets the aforementioned communication requirements, as it can offer a minimum cycle time of <= 1 ms, a maximum number of nodes of 2007 per device, a maximum range of 150 m between each node, and a maximum data rate of 11Mb/s. Therefore, the recommended IWSN technology fits the Industrial systems' communication requirements and hence, the recommended IWSN technology option (Wi-Fi) is verified as the most suitable.

4.2.7 Sensitivity Analysis of SPM Automation Inc.'s Case Study

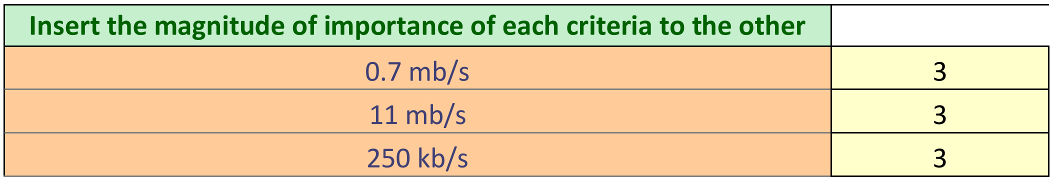
For the purpose of testing and demonstrating the sensitivity of the developed IWSN technology selection/recommendation tool process, the above (original) case study is used again with a different data rate. As shown in Table 3.3, the data rate is assumed to be a non-critical communication requirement; thus, an IWSN technology option with a data rate less than the recommended >10Mb/s can be used in the new case study. This is reflected in the excel sheet ready AHP calculator, where the data rates' magnitude of importance was given an equally lower score for the new case study as shown in Table 4.22 below in comparison to the magnitude of importance scores favoring the recommended data rate for the original case study as shown in Table 4.21 (original case study) below:

Table 4.21 - Data rate's magnitude of importance (Original case study)



Insert the magnitude of importance of each criteria to the other	
0.7 mb/s	6
11 mb/s	9
250 kb/s	5

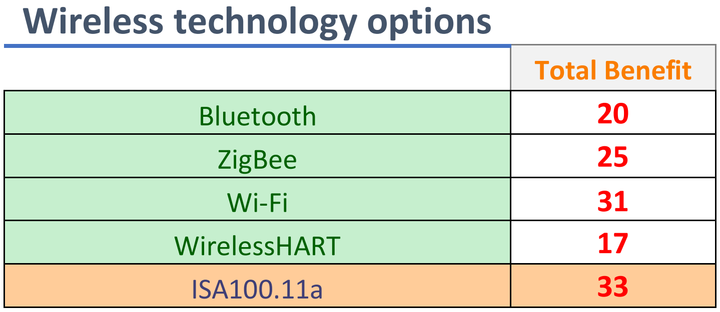
Table 4.22 - Data rate's options magnitude of importance (New case study)



Insert the magnitude of importance of each criteria to the other	
0.7 mb/s	3
11 mb/s	3
250 kb/s	3

Thus, this change represents the sensitivity of the proposed AHP tool, where a slight change of the input magnitude of importance by the user has an impact on the overall recommended IWSN technology option, accordingly, as shown in Table 4.23 below:

Table 4.23 - Recommended IWSN technology (new case study)



Wireless technology options

	Total Benefit
Bluetooth	**20**
ZigBee	**25**
Wi-Fi	**31**
WirelessHART	**17**
ISA100.11a	**33**

In chapter 5, conclusion reached through this research will be provided along with future research work directions.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

This research has introduced a new 6-step selection methodology for industrial wireless sensor networks which utilizes Analytic Hierarchy Process (AHP) techniques and developed an excel sheet ready calculator. The selection process takes into consideration various scenarios that categorizes industrial equipment according to their automation, control types, etc., different application areas, different classes, communication traffic types as well as their communication requirements. This selection strategy was never implemented in previous research and it has been proven that by considering the aforementioned attributes and specific communication requirements concerning cycle time, data rate, range and number of nodes in an industrial system, it is capable of supporting a decision that guarantees selecting the most suitable IWSN technology option. Furthermore, the readily available excel sheet AHP calculator can be applied to any industrial system by considering the specific industrial equipment/machines and their characteristics / communication requirements, inputting into the AHP calculator their magnitude of importance scores (ranging from 1-9) according to their class, communication traffic type, scenario and provided communication requirements. In addition, a prioritizing protocol is presented in cases where the final IWSN technology options' scores are identical or fairly close, which directs the user to further steps to be taken to determine the best fit option.

The developed tool is generic and is not limited to a certain industry, enabling it to be applied to different industries such as an assembly line formed by a group of robots, or a manufacturing facility specialized in machining operations (e.g. facility formed of turning and milling workstations, facility with robots, CNC machines and packaging machines etc.). The obtained final results for a considered application will be then specific to the industrial system relative importance scores.

5.2 Significance

The fourth industrial revolution is one of the most important topics in manufacturing industry and is seen as the future of manufacturing. Thus, this research is beneficial as a step forward, in the transformation process of manufacturing towards a more digitalized and better connected/communicating cyber-physical system; thus, enhancing attributes such as flexibility, reconfigurability, scalability, etc. in an industrial environment easing the manufacturing industry's shift towards implementing industry 4.0.

5.3 Future Work

This research considers only the first phase of implementing an industrial wireless network technology, which is identifying which would fit an industrial systems' requirements. One limitation in this research is the exclusion of cellular networks as a wireless communication option. Therefore, future work could include cellular networks as an IWSN technology option. Furthermore, a further detailed analysis could be performed that considers more factors such as costs related to power consumption and sensor technologies to establish a comparison between the recommended IWSN technologies.

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