WIRELESS COMMUNICATION PROTOCOLS AND STANDARDS INTEGRATION AS PART OF CONTROL SYSTEM ARCHITECTURE: FEATURE AND BENEFITS

Dr. Ulagwu-Echeu A.C.
Industrial Project Resources & Operational Supports Ltd. (IPROS LTD) Corresponding
Email: aulagwu@yahoo.com, Tel: +2347035125272

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Abstract

Wireless Networked Control Systems (WNCS) consist of spatially dispersed sensors, actuators, and controllers interconnected through wireless networks. They are increasingly indispensable in critical control systems within industrial settings due to their notable advantages, including enhanced flexibility, reduced deployment and maintenance expenses, and potential for heightened safety measures. This paper offers a comprehensive overview of WNCS. It begins with an examination of fundamental control system formulation, followed by an exploration of wireless communication and control system networks. Additionally, the paper outlines the architecture of WNCS, highlighting its benefits, trade-offs, constraints, and proposed solutions. Furthermore, the protocols and standards relevant to WNCS integration, conducting comparisons to derive findings and recommendations that facilitate optimal wireless control network communication were achieved.

Keywords: Wireless, Communication Standards, Protocols, Control System, Constraints

1. INTRODUCTION

Creating an ideal control system is crucial for every process business in various industries such as chemical, mechanical, energy etc. Since the automation used in these sectors is based on traditional methods like Programmable Logic Controller (PLC),it is not particularly efficient. There are two negative effects of this (Juneja et al., 2020). The first is the inability to manufacture goods of a suitable quality, and the second is the excessive use of chemicals, water, and other energy sources as a result of poor communication channels (Azhad, 2020). Therefore, greater attention must be paid to this area to reduce the demand for additional resources and labour while increasing the process industries' economic and productive aspects. This may be accomplished by utilising enhanced contemporary control system communication protocols and standards to optimise a variety of design characteristics (Juneja et al., 2020).Using a control loop, a control system directs, governs, or regulates the behaviour of systems or devices. It might be as little as a thermostat-controlled home heating control device or as big as an industrial control system. A feedback controller is used to continuously control how these processes are modified. To get the process variable's output to equal the intended value, the control system compares the value or state of the variable it is controlling to the desired value and uses the difference as a control signal (Anssari, 2021).Using a control loop, a control system directs, governs, or regulates the behaviour of systems or devices. It might be as little as a thermostat-controlled home heating control device or as big as an industrial control system. A feedback controller is used to continuously control how these processes are modified. To bring the output of the process variable to the same intended value, the control system compares the value or state of the variable it is controlling with the desired value and uses the difference as a control signal (Anssari, 2021; Nise, 2020).Real-time assurances are needed for the majority of multi-loop wireless network control system applications now in use, real-time communication via wireless sensor networks is necessary, and energy consumption is kept to a minimum.

1.1 Wireless Communication

The use of wireless communication in daily life has become essential. A growing number of wireless and mobile communication services and applications are emerging (Li, 2021). Any type of radio computer network that combines with a telecommunication network and allows network nodes to connect without the need for wires is referred to as a wireless network. The wireless body area network, wireless personal network, wireless local area network, wireless metropolitan area network, and wireless wide area network may be categorised based on the network's coverage (Chen, 2018). In daily life, wireless LANs and personal networks are the most commonly seen (Islam and Jin, 2019).The establishment of a link between the two communicating parties via electromagnetic waves that are travelling through the atmosphere is the most notable aspect of wireless communication. Users of communication benefit from this in terms of ease and liberty. Electromagnetic waves, on the other hand, are widespread and radiative. As it spreads, it is simple to intercept (Nwazor and Audu, 2022).This paper presents a review of applying wireless communication protocols and standards as a part of control system architecture while also identifying the features of these networks and their benefits in the system. The work is aimed at the provision of insights into the technologies/techniques which can be adopted for the development of an adaptive system in control systems based on wireless communication technology. The paper organizations are as follows;

i. Review of literature on wireless network control system
ii. Overview of control system network
iii. Wireless communication and network control system
iv. Overview of wireless network control system, benefits, trade-off, constraints and solutions.
v. Overview of wireless network protocols, comparative analysis and findings
vi. Overview of wireless network standards, comparative analysis and findings

2. LITERATURE REVIEW

Gautam et al., (2021) reviewed on the evolution and future potentials for the technology of networked control system. The comprehensive review on the NCS technology which discusses the technology in 3 phases which includes the NCSs prior to 2000, NCSs between 2001–2010, and NCSs from 2011 onwards. The transition of control system operation from continuous domain to networked domain, then the practical applications of the modern technology which is based on NSC is also discussed. The study identified that the field of work has a limitation in terms of real-time implementation and recommends that future studies consider real-time implementation.Zhang et al., (2020) surveyed on the trends and techniques of networked control system. The survey presented by this study is aimed at the identification of the trends in the NCS technology. The survey focused on addressing the five control issues associated with the field which includes sampled-data control, quantization control, networked control, event-triggered control, and security control. The work concluded by presenting the need for considering data security which involves data confidentiality for privacy protection in the NCS system. Nwazor and Audu (2022) researched on data communication network for real-time implementation of industrial control systems. The study identified two approaches which can be adopted for implementing the real-time industrial control system operation. The first approach considers system-level interaction over 2 wire networks called collaboration network and the second approach considers the Virtual Local Area Network (VLAN) which allows the real-time control of the services that have the same PortID on the VLAN switch. The outcome of the study identified that the usage of two-wire collaborative network approach has an effective impact on real-time control system but it requires additional network combined with the main data traffic channel. Park et al., (2017) surveyed on the design of wireless network for control systems. The study first discusses the critical interactive variables which include message delay, sampling period, network energy consumption and message dropout,the mutual effects of applying the communication and control variables for motivating their joint tuning,as well as the analysis and design of the control systems which considers the effect of the interactive variables on performance of the control system. Furthermore, the effect of controllable protocols on the probability distribution of the interactive variables are also discussed. The work is concluded with identification of the state-of-the-art design of wireless network and optimization of the wireless networked control system and presentation of major research issues in the field of study. Zhao et al., (2015) presents the communication basics and control methodologies of the networked control systems. The study presents some of the control approaches and theories applied for NCSs such as time delay systems, stochastic control, optimal control and switch system theory. Then, the design approaches for NSCs are such as packet-based control approach and control and scheduling designs are presented as well. The details provided in this research are aimed at provision of assistance to further studies on the field of study.

3. Foundation of Control System: An overview

A control system is a configuration created by joining parts which holistically collaborate to produce an output response. The foundation for control system analysis is a linear transfer function which suggests a cause-and-effect link for the elements of a system (Majumder and Fernandez, 2020).

Control system is classified into two main categories which are open loop and close loop system;

3.1 Open Loop System

In an open-loop control system, a process variable is influenced by one or more system input variables. Because the process variable's actual value is not verified, the open loop control mechanism is unable to account for potential fluctuations, including those brought on by disturbances. Thus, one characteristic of open loop control that sets it apart is an open action flow (Azhad, 2020; Anssari, 2021). This is because the system's inputs are unable to determine if the output is the intended response, open control systems are particularly helpful when the system's prediction rate of outputs is high and the system is generally safe. The transfer function G(s) of an open loop first order system is formulated as;

$$G(s) = \frac{k}{s(T_S + 1)} \quad (1.0)$$

Where K is the system gain, T is the constant time and s is the system variable complexity. In a discrete time domain, the function changes to G(z) as;

$$G(z) = \frac{Y(z)}{U(z)} \quad (2.0)$$

Where Y(z) is the z-th transfer output of the system, U(z) is the system input transfer function and Z is the complex domain.

3.2 Closed Loop System

A closed-loop system is a type of control system where the output of the system is fed-back to the input. In a closed-loop system, the input is adjusted based on the difference between the desired output and the actual output, as measured by the feedback mechanisms. This feedback loop allows the system to regulate and adjust its behaviour in response to changes in the environment or disturbances. The controlled variable in the closed-loop control process is constantly observed and contrasted with the reference variable. The outcome of this comparison affects the system's input variable, which modifies the output variable to the intended value despite any disruptive circumstances. This feedback leads to a closed-loop action. The closed action flow of closed-loop control is characterised by the controlled variable's continuous effect along the action path of the control loop (Majumder and Fernandez, 2020).When a system is closed, sensors monitor the output and link the input to the sensor readings so that the input can be changed in response to output measurements. For this reason, another term for comparable systems is feedback control systems. Since the sensors detect the system's output properly under ideal circumstances, the feedback is represented by the symbol (y(t)). The error coefficient (e(t)) is the result of deducting the value of (y(t)) from the input using an aggregation node. To address the error, attach it to a microcontroller. The microcontroller will then generate a new value that can be input into our facility or system; this new input is represented by the symbol (u(t)), and the input we give the system is known as the reference signal, which has the symbol (r(t)) (Anssari, 2021). The system is depicted in the Figure 1;

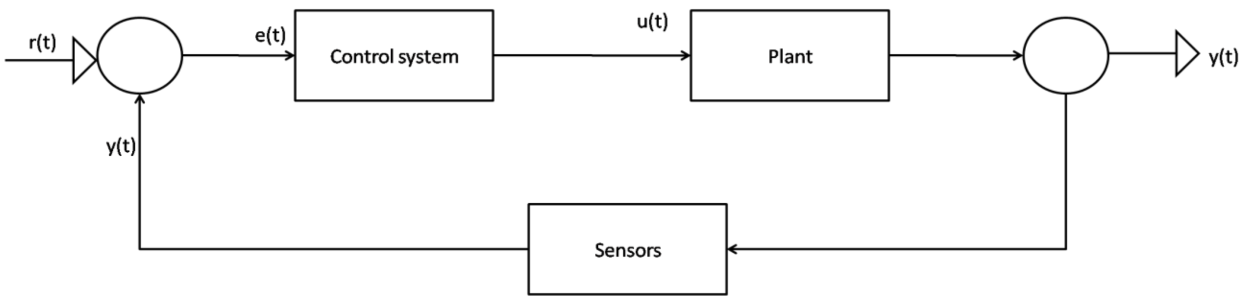

Figure 1: Closed loop control system (Anssari, 2021)

An open-loop approach offers an advantage over closed-loop control in terms of complexity for the driving and sensing electronics since it just uses driving circuits. On the other hand, open-loop driving is susceptible to input signal form and parameter uncertainty. The precise timing of the input voltage spikes is required. For the device under investigation, the precision of the triggering time is often less than 0.1 seconds. Further accuracy is required to achieve higher voltages and faster responses. Closed-loop control generates an oscillation-free response and is less susceptible to changes in system parameters (Planeus, 2021).

4. WIRELESS COMMUNICATION AND NETWORK CONTROL SYSTEM

Wireless communication has revolutionized the field of control systems, offering flexibility, scalability, and cost-effectiveness in various industrial and automation applications. In control systems, wireless communication refers to the transmission of control signals, sensor data, and other information between different components of the system without the need for physical wired connections. This advancement has significantly expanded the scope and capabilities of control systems, enabling remote monitoring, real-time control, and distributed control architectures (Kaur, 2018).A Networked Control System's (NCS) primary functions include giving users access to a communication system that is meant to collect data in real-time. The network protocol, traffic, routing, and ensuring effective exchange of data must all be considered. According to Gupta and Mo-Yuen (2010), networked control is also utilised to create control techniques that reduce potential issues with network performance, delays, and system performance-affecting characteristics.NCS is made up of control loops connected by communication networks, where the system/plant and the controller exchange control and feedback signals. To design NCSs, there are two different approaches: control over network approach and control of network approach. This evaluation only takes into account the control over network approach-based NCSs (Gautam et al., 2021). The sensors of an NCS are used to measure the plant output. The Analogue-Digital (A/D) converters transform these impulses into digital signals, which are then sent across a communication network to the controller. Using the same communication channel, the controller uses the sensor output to determine the control signal, which is then sent back to the plant. The Digital-Analogue (D/A) converter transforms the control signal from digital to analogue before feeding it to the plant's actuator section. This allows for remote control of the plant dynamics (Gautam et al., 2021; Park et al., 2017).

5. WIRELESS NETWORK CONTROL SYSTEM (WNCS)

The WNCS involves a process design architecture powered by wireless communication system. The process design is the components of the process control system such as the actuators, sensors and then the basic process control system which is the controller. These components are communicate with each other using a standard wireless protocol which enable s seamless file exchange. The Figure2 showcased the main layer of the WNCS.

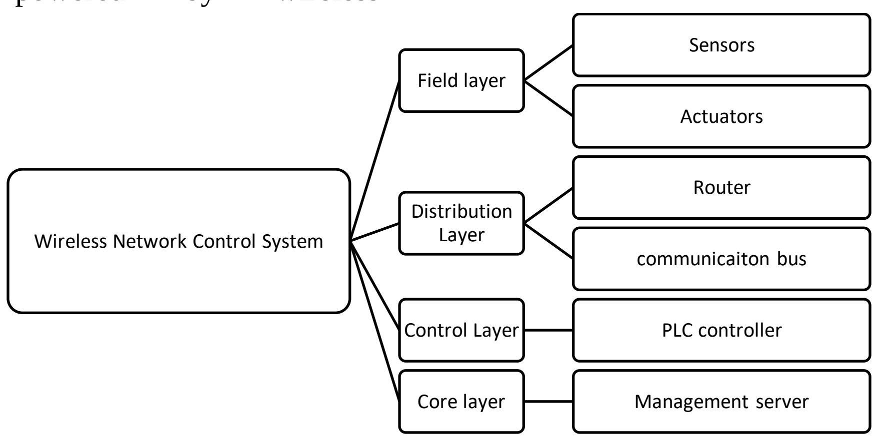

Figure 2: Block diagram of WNCS

The Figure 2 showcased a WNCS with four main layers which are the field layer responsible for the management of the process design components such as the sensors, actuators, remote telemetry unit, which are devices which collected data from the field plants and then remotely send to the distribution layer for transfer using the router through the communication bus. The router is the devices which utilized routing protocols to enable seamless data transfer and communication between components. The control layers take care of the industrial automation process using the information received remotely from the process design components and then store in the core layer for data analysis and management.When compared to the traditional wired control system network, the benefit of the wireless are listed as follows (Wang and Liu, 2008; Park et al., 2017):

i. **Lower deployment and maintenance costs:** Because WNCSs do not require significant wiring, the complexity and total cost of developing and deploying control systems are reduced.
ii. **Flexibility**: The addition of sensors, actuators, and controllers to WNCSs may be done at a reasonable cost and without requiring significant structural changes.

iii. **Enhanced safety**: Where cable control systems are impractical, such as in hazardous situations like space and terrestrial exploration, WNCSs can be employed.

iv. **Efficient sharing of data**: WNCSs have effective data exchange across their controllers, which make it simple for them to combine worldwide data and make deft judgements over sizable physical areas.

v. **Wide range of applications**: Many sectors, including industrial automation, remote diagnostics and troubleshooting, experimental facilities, household robots, aeroplanes, cars, manufacturing plant monitoring, and nursing homesmight benefit from the use of WNCSs.

5.1 Trade-off and Constraints of Wireless Network Control System (WNCS)

Trade-offs is inherent in decision-making processes, particularly in engineering. In the context of WNCS, trade-offs involve decisions that need to be made regarding conflicting factors such as reliability versus latency, range versus interference, security versus performance, and others as shown in the Figure3.

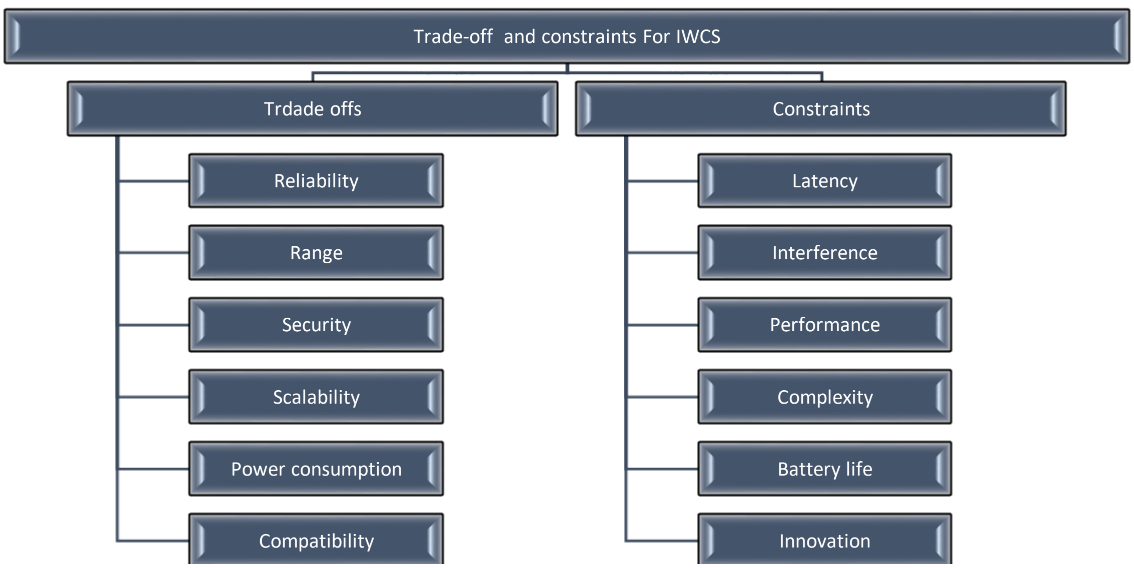

Figure 3: Trade-offs and constraints for IWCS

The Figure 3 showcased IWCS tradeoffs and equivalent constraints. The trade-offs encompass crucial elements such as reliability, ensuring a system's consistent and accurate performance; range, defining the distance covered effectively; security, safeguarding against unauthorized access and data breaches; scalability, allowing flexibility and growth; power consumption, managing energy resources efficiently; and compatibility, ensuring seamless integration with diverse components (Qiang et al., 2020). However, these trade-offs operate within the boundaries set by specific constraints. Latency, the time delay in data transmission, is a critical constraint that impacts real-time responsiveness. Interference, both internal and external, poses challenges in maintaining signal integrity(Peng and Sun, 2020). Performance constraints dictate the overall efficiency and effectiveness of the system. Complexity is another limiting factor, influencing the ease of use and maintenance. Battery life is a fundamental constraint, especially in wireless systems, where prolonged operation is crucial. Lastly, innovation constraints encapsulate the challenge of incorporating novel technologies while ensuring compatibility and reliability in the system(Liu and Liu, 2020).

5.2 Suggested solution to the constraints

The suggestion solution to the issues of latency are the integration of optimal routing algorithm, load balancing techniques, priority queuing of packets and congestion control mechanisms to manage the issues of latency on the network(Zhang et al., 2020). For the case of interference which occurs due to the multiple signal transmission among components colliding, the need for an interference management scheduling scheme is necessary to coordinate the flow of signal and ensue that signal from diverse sources do not flow through the same channel at a time (Alobaidyand Awad, 2023). Performance of the network can be improved using updated network infrastructures in the hardware and software domain, while the complexity issues can be addressed with a well-defined network topology that structures the position and role of each component appropriately. Battery life can be controlled with energy management techniques which consider the activity of the network components to control how energy is managed (Deng et al., 2020).Overall these recommendations seek to address the identified challenges experience in the WNCS and guarantee quality of service.

6. PROTOCOLS FOR WNCS

WNCS has several standards that are crucial to the creation and use of dependable and effective control systems. In the functioning of industrial systems, these protocols and standards provide a high degree of interoperability, dependability, and security. The following are some of the procedures that WNCS has embraced (Bhatia et al., 2022; Zhao et al., 2015; Millan et al., 2011): the Figure4 showcased the various WNCS protocols.

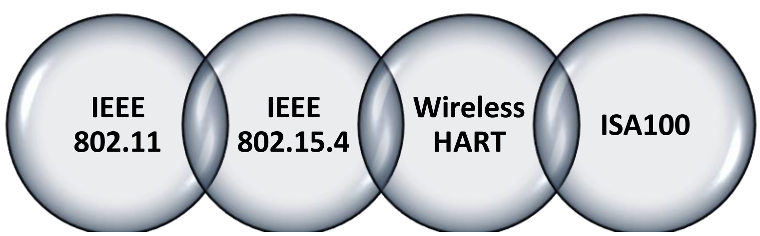

Figure 4: Wireless network protocols

6.1 IEEE 802.11 Protocol

Due to data packets between controllers, real-time control is a crucial element to take into account while implementing control over a WLAN (Wireless Local Area Network). Periodically transmitting sensors and actuators is necessary to reduce transmission loss and error (Joshi et al., 2023). Despite not being intended for WNCS applications, the IEEE 802.11

protocol might be helpful for network control when the Distributed Control Function (DCF) is set. The WLAN nodes decide among themselves which station can broadcast using this protocol. To prevent collisions, each station has to verify the channel state before transmitting. The station can transmit in a random back-off time interval if the channel is idle over a certain period (Diaz et al., 2020).

6.2 IEEE 802.15.4 Protocol

ZigBee is a high-level standard for Wireless Personal Area Networks (WPAN) that is based on IEEE 802.15.4. It describes the medium access control and physical layers of low-data-transmission wireless networks. Because the 2.4GHz frequency has a 250Kbps channel capacity, ZigBee is meant to operate at low speeds. El-Gholami et al. (2021) highlights the expense of communicating with adjacent nodes in the absence of a sophisticated infrastructure to ensure minimal power consumption.

6.3 WirelessHART

When it comes to obstructions and interferences, industrial settings are more challenging for wireless applications than office settings. With a focus on wireless instrumentation for the industrial automation sector, WirelessHART is a TDMA-based, secure wireless mesh networking solution that operates in the 2.4GHz Industrial, Scientific, and Medical (ISM) radio band (Du and Guo, 2022). Based on IEEE802.15.4, WirelessHART devices employ a pseudo-random channel hopping sequence to lessen the possibility of interference with other networks, such as IEEE802.11b/g (Wi-Fi), which uses the same ISM frequency range as WirelessHART.

A WirelessHART network can maintain high data reliability while minimising if not eliminating, any impact it has on other overlapping networks by utilising techniques like time division multiple access, channel hopping, mesh networking, low power, and direct sequence spread spectrum coding (Caballero et al., 2020; Abolateb et al., 2022).

6.4 ISA100

Similar to WirelessHART, ISA100 is designed to offer dependable and secure wireless operation for supervisory control, alerting, and non-critical monitoring. It is based on IEEE 802.15. Low power consumption, immunity to interference, and device interoperability are important characteristics (Zhao and Ouyang, 2022). In addition to being a TDMA-based wireless mesh network, ISA100.11a can handle many protocols over a single wireless infrastructure (Raptis et al., 2020). Table 1 comparatively analysed the WNCS protocols;

Table 1: Comparative analysis of network protocols

Protocol	Application	Findings	Speed	Frequency
IEEE 802.11 Protocol	WLAN	Real-time control is crucial. Periodic transmission reduces errors. DCF aids in network control.	High	2.4GHz
IEEE 802.15.4 Protocol	ZigBee (WPAN)	Low-speed operation due to 250Kbps capacity. Power consumption concerns in node communication.	Low	2.4GHz

Wireless HART	Industrial Automation	TDMA-based secure networking. Uses 2.4GHz band. Minimizes interference with channel hopping.	High	2.4GHz
ISA100	Supervisory Control, Monitoring	Offers secure wireless operation. Low power consumption. Capable of handling multiple protocols.	High	2.4GHz

From the Table1 summarizes the different protocols used in wireless communication, it reveals diverse range of wireless protocols catering to various applications, each with its own strengths and considerations regarding speed, frequency, security, and power consumption. These findings underscore the importance of selecting the appropriate protocol based on the specific requirements of the intended application.

7. Standards for WNCS and their characteristics

The most widely used standards in the wireless communication business are ZigBee 802.15.4, WLAN 802.11, and WPAN Bluetooth 802.15.1. These protocols operate in the 2.4GHz ISM band, and modern industrial installations may allow them to coexist. The Figure5 showcased the main standard for WNCS while the main characteristics of these standards are shown in Table 1 (Millan et al., 2011).

Figure 5:Standards for WNCS

The Figure 5 presents the WNCS standards such as ZigBee 802.15.4, WLAN 802.11, and WPAN Bluetooth 802.15.1. These standards are discussed as;

7.1 Bluetooth/IEEE 802.15.1

The Bluetooth standard which is regulated by the IEEE802.15.1 is designed to facilitate short range communication process, especially for PAN personal area network devices. Its versatility extends to industrial applications such as sensor connectivity, monitoring of equipments within a confined space (Peng and Sun, 2020). The application of this Bluetooth standard for industrial communication was further facilitated due to its low energy consumption and ubiquity makes it indispensable for industrial application.

7.2 ZigBee/ IEEE 802.15.4

This standard for industrial communication has emerged as a cornerstone for the Wireless Personal Area Network (WPAN), particularly for low data demanding and power requirements applications. This standard facilitates scalability and robust communication in not only industrial settings, but also smart homes, and building management systems(Peng and Sun, 2020). The standards which operated at 2.4 GHz and 868/915MHz bands provide flexibility in deployment while minimizing interference. Due to its many benefits such as compatibility for short range component communication, low power requirements, speed and low data rate, it has remained one of the most utilized standard for industrial wireless communication.

7.3 WLAN/ IEEE 802.11a/b/g

This standard for Wireless Local Area Network (WLAN) with characteristics such as high data rate, extensive coverage, seamless internet access, real time data communication, multi-media streaming is another popular standard for industrial and commercial application settings (Liu and Liu, 2020). This standard excels in supporting bandwidth intensive applications and ensue high speed communication in critical industrial automation settings. The Table2 was applied to compare the three standards for industrial wireless communication systems.

Table 2: Standards for WNCS and their characteristics (Zhang et al., 2020)

Characteristic	Bluetooth/IEEE 802.15.1	ZigBee/ IEEE 802.15.4	WLAN/ IEEE 802.11a/b/g
Range	10 (50- 100m)	10m	50-100m
Data rate	723 Kbit/s	125 Kbit/s	2.6 Mbit/s (60 bytes payload), 30.6 Mbit/s (Ethernet)
Interoperability	High	Moderate	Moderate
Power usage	Low	Very low	Moderate
Periodic data	Indeed, contingent on the polling algorithm.	Yes	DCF: no; PCF: yes, but erratically; HCF: yes
Forward Error Correction (FEC)	Available	No	No
Use case applications	Personal Area Networks (PANs)	Home automation, smart homes, energy management	Internet, multi-media, enterprise network, VOIP
Transmissions	Yes	Yes	Yes
Topology	Support star network	Support star and mesh network	Ad-hoc network
Security	Basic security features like authentication and encryption	Authentication, encryption, network security and message integrity	Advance encryption, access control
The quantity of devices in the network	Low	Moderate	High

7.4 Findings and Suggestions for the System Application

From the comparative analysis of the three standards for industrial wireless communication systems, it was observed the each of the standards has its positives and setbacks, based on their characteristics. What this means is that the user device for the process design architecture considering components types, position, distance, compatibility will determine the type of standard to be adopted. For instance, in a simple control system network, the Bluetooth and ZigBee can be the best for communication due to their low energy, and success for short range communication. Meanwhile, for large distribution control network which requires large scale communication across section of the process design, the WLAN/ IEEE 802.11a/b/g standards stand out as the best due to its ability for real time communication, wireless connectivity and quality of service requirements. Overall, the most commonly used protocols for system integration are; ISA100, WirelessHART which is used for process automation, ZigBee, which ensures low-data rate and low power consumption in the wireless communication protocol, Bluetooth Low Energy (BLE), used for building control systems for home automation, WLAN connectivity which ensures the fluent flow of communication protocols in the system network. Then, there are various standards which are applied for the integration of the wireless networked control systems. These standards define how the wireless networks operate after being integrated into the control system. An example of the standard is the Wireless Local Area Network-Network Interface Card (WLAN-NIC) when implemented on the IEEE 802.11b standard, the wireless NIC will be able to only interface with the infrastructure of the 802.11b standard.

7.5 Research Contribution

This paper significantly contributes to the understanding and advancement of Wireless Networked Control Systems (WNCS) within industrial contexts. Through a comprehensive examination, it elucidates the foundational principles of WNCS, explores the intricacies of wireless communication and control system networks, and outlines the architecture of WNCS, including its benefits, trade-offs, and constraints. By analyzing protocols and standards for WNCS integration, the paper offers valuable insights and recommendations for optimizing wireless control network communication. Overall, its contribution lies in providing a holistic overview of WNCS, offering practical guidance for deployment, and facilitating the realization of enhanced flexibility, cost-effectiveness, and safety within critical control systems in industrial environments.

8. CONCLUSION

This paper presented an overview of Wireless Networked Control Systems (WNCS) and their significance within industrial control systems. It has explored the foundational principles of control system formulation, delved into wireless communication technologies, and examined the architecture of WNCS, highlighting its benefits, trade-offs, and constraints. However, challenges such as latency, reliability, and security remain pertinent considerations that necessitate further research and innovation were identified and solution to manage them suggested. Furthermore, the protocols and standards for WNCS integration such are IEEE 802.11 protocol, IEEE 802.15.4 protocol, WirelessHART and ISA100 are equally discussed, comparatively analyzed. Ultimately, the successful implementation of WNCS promises to yield substantial benefits, paving the way for more efficient and resilient industrial operations in the digital age.

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