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Analysis and Challenges in Wireless Networked Control System: A Survey

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ABSTRACT

A wireless networked control system (WNCS) consists of a dynamic system to be controlled, sensors, actuators, and a remote controller. A WNCS has two types of wireless transmissions, i.e., the sensor's measurement transmission to the controller and the controller's command transmission to the actuator. In this paper, we are surveying the literature on the communication networks in WNCSs and the challenges related to them, such as the communication standards, delay, Packet dropout, and delay jitter. Then, the control approaches in the design of a WNCS are presented, including the interactive design approaches and the joint design approaches. Also, several applications of WNCSs have been discussed in terms of their structure, functionality, and control design. These applications include Intra-Vehicle Wireless networks, Wireless Avionics Intra-Communication, Building Automation, and Water pumping. After that, security issues in WNCSs from a control engineering point of view are detailed while focusing on the major kinds of cyber attacks affecting WNCSs. Finally, future directions and conclusions are summarized at the end of the paper.

1. Introduction

A Wireless Networked Control Systems (WNCS) is a networked control system that uses a wireless communication for transmitting signals among the system components between different nodes. In other words, the controller in the WNCS communicates with sensors and actuators over wireless channels. In this network, the controller receives the measurements' signals sampled by the sensors that are attached to the plant over a wireless channel. Then, the control signals are generated by the controller and transmitted to the actuators over a wireless channel to affect the dynamics of the plant [1], [2].

The interaction between control systems and information and physical plants increases dramatically due to the continuous improvement in computing, control, sensing, and wireless networking [3]. This clearly appears in the recent fields and applications that require control of the physical system in real-time such as Tactile Internet, Internet of Things (IoT), and Cyberphysical Systems (CPSs) [4, 5, 6].

The implementation of WNCSs becomes very useful due to the increase in the demand for distributed applications such as transportation, manufacturing, and power generation. Some advantages of the WNCSs are the flexibility in the distribution of the nodes, reducing the maintenance efforts required in wired communication, in addition to the benefit of using mobile nodes in several applications [7]. WNCSs have many advantages such as their flexibility, better safety, and ease of installation and maintenance.

Fig. 1 shows a typical model for a WNCS that consists of a physical plant, sensors, actuator, controller, and wireless channels. The surge of technologies like cloud computing, advanced control, wireless networks, and embedded computing pushes the development of WNCSs. Additionally, there was a need for this development to emerge applications in industrial automation [8, 9], building management [10], avionics [11], and automotive [12, 13]. Recently, WNCSs have a great role in the evolution of Industry 4.0 [14]. Many international organizations support the implementation of WNCSs. Some examples are: wireless Industrial Networking Alliance [15], Highway Addressable Remote Transducer (HART) communication foundation, International Society of Automation [16], Z-wave Alliance, ZigBee Alliance, Wireless Avionics Intra-Communications Alliance [11].

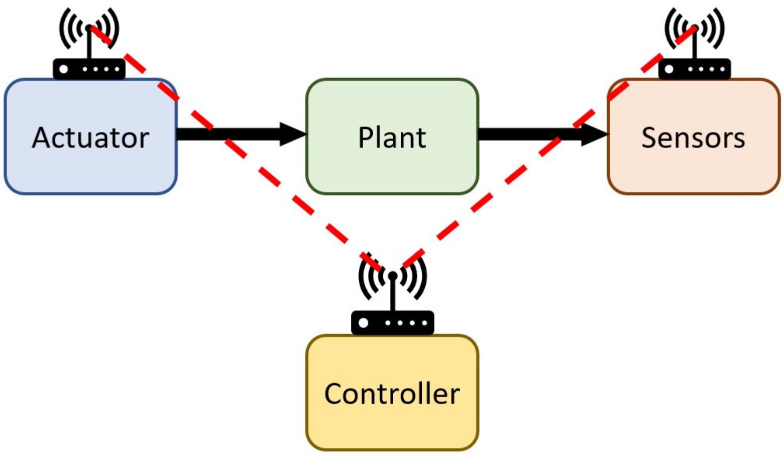

Fig. 1. A model for a WNCS

Several topics related to WNCSs were considered theoretically and practically in the current research. Some examples of these topics are: a decentralized event-triggered method in the presence of wireless networks for sensor and actuator [17], sensor networks [18, 19], multiagent systems [20, 21], the dynamics of aircraft [22], automation of factories by the implementation of wireless networks [23], the maximum area covered by a WNCS while taking account of the estimator's convergence [24], and joint optimization of communication and control systems with the minimization of the consumed power by the communication system [25].

One of the issues discussed in the literature is the topology applied to WNCSs. In general, three kinds of systems are implemented in WNCSs which are [7]:

1. A physical system with multiple nodes for sensors and actuators.
2. A control system with multiple nodes for input and output terminals.
3. A WNCS with joined nodes and wireless communication channels.

The nodes of both the WNCS and the physical plant are connected by communication channels. The physical system is controlled solely by the nodes of the WNCS which is independent of any dedicated control system and has the ability to perform simple computational tasks [7]. The advantages of the topology include providing simple communication scheduling and computational tasks. The capability of expanding the scale of the control system and using multiple sensors and actuator nodes was presented in [26]. Intrusion detection system is discussed in [27], associated topological conditions were investigated in [28, 29], the typology's model and design working in perfect circumstances with unreliable communication channels and nodes were presented in [30, 26, 31].

The design and definition of the topology were detailed in [32]. In [33], associated design considerations including joint design and model reductions were discussed. A design for a topology for unreliable situations was proposed including the unreliability in the nodes of the sensors, actuators, and the controller and the unreliability in the communication channels among all of the nodes [7].

Much literature discusses the development of WNCSs. Remote control methods for various applications employing the internet were discussed such that the interaction between control and computing theories was considered in [34]. A review of the real-time wireless sensor-actuator networks (WSANs) in applications related to the industry is presented in [35]. This review includes analysis and algorithms implemented in WSANs, the application of the protocols, and the co-design of WNCSs. A theoretical alternative for industrial IoT applications is provided using the methods of stochastic control [36], the effect of the channel occupancy, the configured communication protocol, and the delay in the system can be evidenced. The network in this work could be a remote, local, or cloud system, and its behavior is obtained using the simulation through several libraries. A comprehensive survey of the crossovers between deep learning and wireless networking is presented [37]. Moreover, a survey on the deployment of deep learning onto mobile systems and the mobile and wireless networking research based on deep learning were discussed.

In this article, we focus on each part of the WNCS such as the communication network, control design, some applications, and security issues in WNCSs. The research contributions are summarized in the following points:

- A review of the standards of the communication network in WNCSs and the related problems are presented including wireless communication standards, packet delay, packet drop/loss, end-to-end connection type, delay jitter, and fading.
- Several approaches of control design in the WNCSs are discussed including the interactive design approaches and the joint design approaches.
- Special applications of WNCSs were discussed in terms of their structure, functionality, and control design. These applications include intra-vehicle wireless networks, Wireless Avionics intra-communication, Building Automation, and Water pumping.
- The security issues in WNCSs are summarized including the several kinds of possible cyber attacks affecting WNCSs such as DoS attacks, deception attacks, jamming attacks, replay attacks, and spoofing attacks.

The remaining of this paper is summarized as follows: in section 2 the communication network in WNCS is discussed. The control design in WNCS is reviewed in section 3. In section 4, several applications of WNCS are presented. Then, security problems in WNCS are listed in section 5. Finally, conclusion and current directions are summarized in section 6. The structure of the paper is shown in Fig. 2.

2. Communication network

The following example illustrates how the wireless channels interact with the control systems [3]: a single-hop wireless networking protocol IEEE 802.15.4 is used for connecting sensors with a controller in a WNCS [38]. The sum of the deviations of the plant state from the desired set-point and the magnitude of the control input is selected as the quadratic control cost. In the example, the maximum allowable cost for the control is chosen as 6, which is not feasible due to the limitation of the protocol applied here. In general, if a delay occurs in the message, and the sampling period and loss probability increase, the control cost also increases. This means that applying short sampling periods will lead the delay in the massage and massage loss probability to be closer to the critical values and so the system becomes closer to the instability [39]. In conclusion, one can notice that it is not trivial to achieve feasibility in the WNCS due to the interaction between control and communication systems.

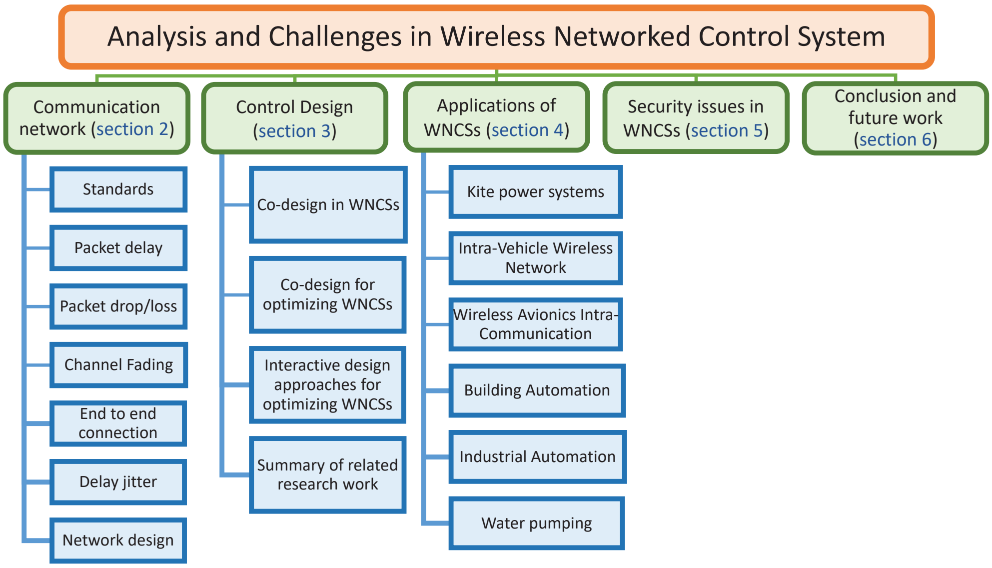

Fig. 2. Structure of the paper

There are several types of wireless networks and their applications. Lower-Power Wide-Area Network (LPWAN) are applied for enabling the connections of IoT over long-ranges (10-15 km). Some examples include NarrowBand IoT (NBIoT) [40] and Long-Range WAN (LoRa) [41]. Moreover, LPWAN-based control applications are applied with WNCSs such as Remote Healthcare [42], Smart Transportation [43], and Smart Grid [44]. The protocols and general requirements of industrial applications with wireless sensor networks (WSNs) is discussed in [45]. A comparison between WSN standards applied in popular industry is provided in terms of design and architecture [46]. Protocols and algorithms' scheduling in real time application for Wireless HART networks for industrial automation are elaborated in [47]. Recently, a detailed survey of WSNs for the design of controllers in addition to the interaction between control and communication designs are discussed in [3].

In the following sub-sections we present several issues related to the communication network in WNCSs.

2.1. Standards Used in Wireless Communication

The most popular standards applied in WNCS are [48]:

1. IEEE 802.11: This standard is applied in WNCSs with data rates of 1, 2, 11, 54 Mbps. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is used as protocol for Medium Access Control (MAC) with IEEE 802.11. It is worth to mention that, protocols using contention like CSMA/CA are not suitable for communication in real time application since the nodes need to make handshaking and packet delay is not guaranteed to be bounded.

2. IEEE 802.15.4/ZigBee: This standard is suitable to short distances which is less than 10m and it comes with two types:
   - High Rate-WPAN (802.15.3): suitable for applications include constraints on quality-of-Service (QoS)and high data rate, so it is useful in multimedia applications. Also, it can handle ad hoc mode.
   - Low Rate-WPAN (802.15.4): suitable in ad hoc mode that consumes less power with low cost. However, the performance characteristic and data rate will be low. It is applicable for 250, 40 and 20 Kbps data.
3. IEEE 802.15.1/Bluetooth: It requires low power and low cost, and a versatility with high degree. It is used in applications related to industry.

2.2. Packet Delay

The performance of the WNCS can be highly affected and even destabilized because of the packet delay in the network [49, 50]. There are several sources of the packet delays such as the traffic in the network, the applied protocol, and the limited data bandwidth [51]. To understand the model of a WNCS with a packet delay, let us consider the total closed loop delay to be τ_{total} and described as follows:

$$\tau_{total} = \tau_{sc} + \tau_c + \tau_{ca} \tag{1}$$

where τ_{sc} and τ_{ca} is the delay in communication between sensor and controller, and between controller and actuator, respectively. And τ_c is the time consumed by the controller. Here, the delay in the controller τ_c is deleted or added to τ_{ca} to simplify the calculation. This assumption is justified because it is negligible and almost constant in comparison with τ_{sc} and τ_{ca} [52, 53]. As a result, the total delay is written as:

$$\tau \approx \tau_{sc} + \tau_{ca} \tag{2}$$

Remark 1 *Based on the occurrence of the delay, there are two kinds of controllers:*

1. *One-mode controller: when the designed controller consider one of the delays. i.e. sensor-to-controller delay or controller-to-actuator delay.*
2. *Two-mode controller: The designed controller consider the two delays.*

In [54, 55], Markov chain method was used to model both of the sensor-to-controller and controller-to-actuator random delays in the system.

Fig. 3 shows the two main types of the packet delay in the WNCS, the sensor to controller delay and controller to actuator delay. Fig. 4 shows the effect of the packet delay on the signals in the different parts of the system.

Following is an example of a WNCS with random communication delays. In this example, the event driven is applied on the controller and the actuator, while the clock driven is used by the sensors. So, the discrete-time linear time-invariant model of the plant is described as:

$$\begin{aligned} x_p(k+1) &= Ax_p + Bw_p, \\ y_p(k) &= Cx_p(k), \\ z_p(k) &= Gx_p(k) \end{aligned} \tag{3}$$

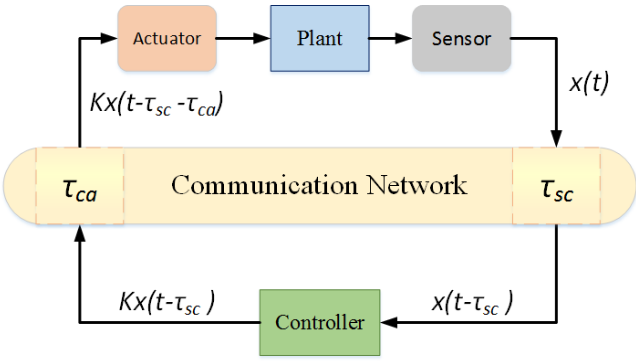

Fig. 3. Packet delayin a WNCS

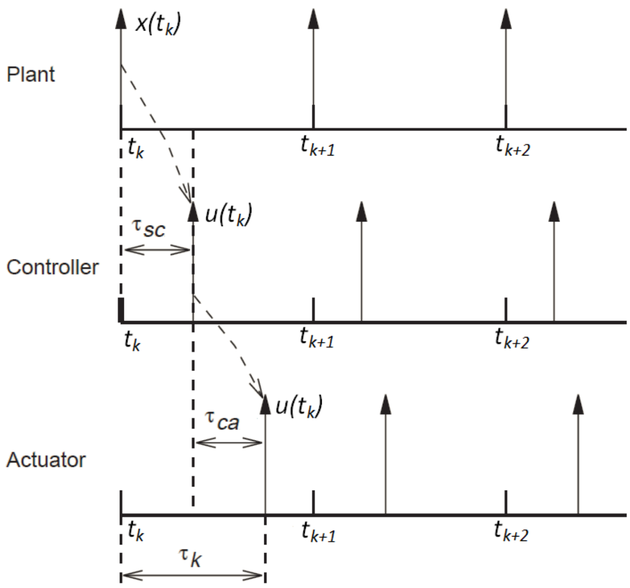

Fig. 4. Signals in an NCS with delays

where $x_p(k) \in \mathbb{R}^n$ is the state vector of the plant and $w_p(k) \in \mathbb{R}^m$, $z_p(k) \in \mathbb{R}^m$ and $y_p(k) \in \mathbb{R}^p$ are the disturbance vectors on the plant's input and output, respectively. The real matrices A, B, and C are with appropriate dimensions and C is a full row rank matrix.

One can consider a general scenario including the measurement with a randomly varying communication delay as follows:

$$y_c(k) = \begin{cases} (y_p(k - \tau_k^m), & \delta(k) = 1 \\ y_p(k), & \delta(k) = 0 \end{cases} \tag{4}$$

where τ_k^m is the measurement delay satisfying the Bernoulli distribution, and $\delta(k)$ is a white sequence with a Bernoulli distribution. The design for a PID controller working remotely in multivariable WNCSs is described in [56, 57].

Remark 2 *The packet delay in WNCSs is normally time varying* [58]*, so it is not practical to apply approaches of control systems that consider the time delay as a constant value. The condition for stabilizing the WNCS can be designed by calculating the maximum delay between any two successive signals in the case of the sampling period T_s is greater than τ* [59, 60, 61, 62]*. And, some delay* *compensation methods can be applied for the other scenario when the sampling period is less than τ* [61].

Several literature consider the packet delay in WNCSs. A scheduling algorithm considering communication delay is presented in [63], the delay of periodic communication tasks in the WNCS in the real time can be tolerated by applying this scheduling algorithm. In [64], packet delay and packet dropout were implemented in the design of a controller in a WNCS while considering various time delay profiles in the system. State estimation problem is solved using sliding mode observer for a kind of WNCS with stochastic uncertainty and time delay [65], sufficient conditions are obtained by applying proper Lyapunov-Krasovskii functional via linear matrix inequality. [66] solves modeling and stabilization problem of a discrete-time WNCS with time-varying delay by designing a static controller using state and output feedback. The parameters of the controller are obtained using the linear matrix inequalities method based the Lyapunov stability theory.

2.3. Packet Drop/Loss

Another feature can affect the transmission of the packets in the WNCSs is the packet drop/loss which also can lead the system to be unstable. If the Re-transmission is applied, more traffic in the channels is produced. This means it is more useful to ignore a packet if it is not sent immediately [67]. The question then, is what is the tolerance of packet drop rate for maintaining the stability in the system?

A two-state switch θ is used for modeling the packet dropout in a WNCS with $\theta \in \{0, 1\}$. Here, the packet is transmitted when $(\theta = 1)$ and lost when $(\theta = 0)$. In this example, if a packet drop occurs in the network, the controller will uses the previous state which was buffered. Packet dropout can be tolerated up to some extent and the stability is maintained in modern WNCS [68, 67, 62].

In general, there are two methods for modeling packet dropouts [69]:

1. The controller is designed while considering the upper bound of the possible dropouts occurring in the communication system.
2. Representing the occurring of the dropout as switch in the communication channel. The dropout happen when the switch is open, and if it is closed, there is no dropout.

The fault detection problem of WNCS with multiple time delay and packet loss is presented in [70]. That packet loss is considered to take place between the controller and actuator, and the fault observer is modeled for a discrete time linear system with time delay. Using Lyapunov function, the stability condition for the observer in this system is obtained in terms of linear matrix inequality.

2.4. Channel Fading

Fading in WNCSs is defined as a deviation of the attenuation that affects a signal over certain propagation media. Fading is modeled is a random process since it is varying with radio frequency, geographical position, or from time to time. When a communication channel experiences fading, it is called a fading channel. Many literature discussed the problem of channel fading in NCSs and WNCSs from different points of view [71].

Following the two main methods applied with channel fading:

- Information theory based method: The capacity of the channel is a very important factor in the information theory. So, the WNCSs with channel fading are studies in the literature from the information theory point of view. The main attention is the effect of the channel on the performance on the control part of the system and the capacity of the channel required to achieve the stability of the plant. The network resources required for achieving the mean square stabilization are designed for stochastic fading channels for MIMO discrete-time systems [72].

- Stochastic system method: Many channel models were applied in fading channels such as Lth-order Rice fading channel, erasure with holder, channel with delay, and analog erasure channel. The model based on Lth-order Rice fading channel in WNCSs attracts many researcher. It is a method for modeling of wireless mobile links and can be represented as follows:

$$r(k) = \sum_{i=0}^{L} a_i(k)v(k-1) + n(k) \tag{5}$$

where $n(k)$ is a white Gaussian noise with zero mean and unit variance. a_i are the i.i.d. Gaussian random variables with mean a_i and variance σ_i^2. And for each k, they are independent from each other and independent from $n(k)$. The closed-loop system of this model is a stochastic system with multiple random parameters and delays.

Nonlinear WNCSs with channel fading and randomly occurring infinite distributed delays were discussed using a fuzzy control method [73]. The lifting approach is applied for transforming the closed-loop system into a delay free system. The envelope-constrained estimating with measurements for fading and nonlinearities occurs randomly is presented [74]. More outcomes could be found in [75, 76].

State estimation using Kalman filter was proposed for a multisensor NCSs in [77]. A random fading in measurements is happened since the sensors transmitthe signals to a remote state estimator using a multiantenna random access network. A simultaneous H_∞ stabilization problem is solved for a distributed WNCS in which a wireless channel is used by the distributed dynamic output feedback controllers for the local measurements and for receiving the neighboring controllers' broadcasts [78]. The Rice fading model is applied for describing the channel fading in the wireless channel. A sufficient condition on the existence of desired controllers and the parameterization of the controller gains are obtained using the Lyapunov functional method and related stochastic analysis techniques.

2.5. End to End Connection Type

There are two main protocol used for communication over wireless networks:

1. Transmission Control Protocol (TCP): This protocol is not appropriate in multi-hop mobile ad-hoc networks (MANET) since it is applying connection oriented packet transfer [79].
2. User Datagram Protocol (UDP): This protocol has low overheads because the connections are not preserved and ignored or dropped packets are discarded. So, it is more suitable in the WNCSs applications [52].

2.6. Delay Jitter

The variation of a part of a signal from the correct position in a defined time or the standard deviation of the measured delays of the packet in the communication network is called jitter. Several problems can lead to a jitter in the system such as number of hops on the path, scheduling of real time tasks in computer systems, routing algorithm in communication systems, congestion, and a drift in the clock of a transmitter-receiver [48].

The jitter in WNCSs is represented as follows:

$$E_j = V_j - U_j \tag{6}$$

where U_j and V_j are the time between j-th and $(j+1)$-th packet arrival and packet departure, respectively. So, the packets clustering that lead to buffer overflow is represented by negative jitter while packets dispersion that lead to excessive delay is considered as positve jitter [80].

2.7. Network Design

various networking challenges need to be defined for achieving a wider acceptance of wireless technology in industrial control. The medium access (MAC) protocol is a network design issue in WNCSs since it determines the communication opportunities.

In general, MAC protocols have two main category:

1. Random access MAC: There is no guarantee for approaching the medium in a given time.
2. Deterministic access MAC: A communication slot is allocated for each node or node-pair either in frequency, time, with code division, or a combination of them. So, approaching the medium could be assured in a predestined time. So, the protocols of deterministic MAC are more suitable in WNCS since it needs to operate in real time mode.

Remark 3 *Although a network applying a protocol of random access MAC is non-deterministic, the interference or fading causes the network to be deterministic MAC protocol* [48].

3. Control Design

The design of the controller in WNCSs requires considering the imperfections and challenges as mentioned in the previous section, such as to be robust in network suffering from delay jitter and packet loss. Systems based on single control loop can be solved analytically and the proofs of the stability will consider the network delay jitter. However, it is much difficult in the case of large control systems with many control loops, or even if a specific network protocols is introduced in the system. Here, the effect of the network and the various protocols on the control system have to be investigated by simulation [48].

Figs. 5-7 shows three main control architectures applied in WNCSs. Only wireless measurements are considered in these architectures since the controller can be attached to the actuator to remove the unneeded links between the controller and actuator. However, the three architectures can be developed easily if the the controller communicate with the actuators by wireless links, but this will increase the difficulty in the design of the controller [79].

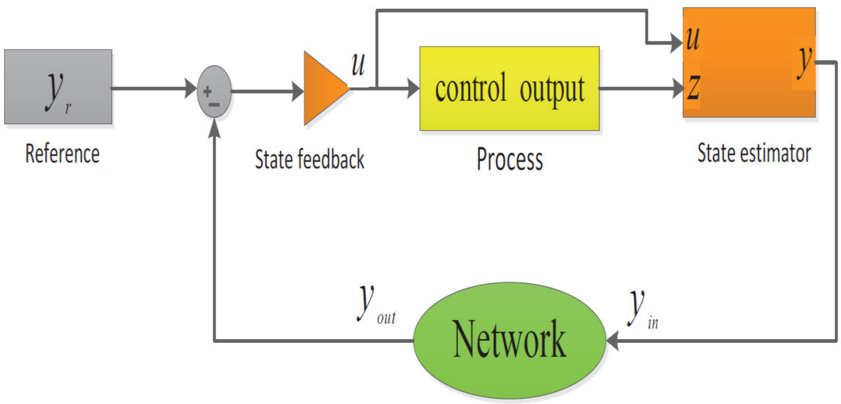

Fig. 5. Optimal state feedback framework in WSCS

The design of a WNCS needs to consider the physical plant, control, computation, and communication parts simultaneously. The implementation of the wireless communication, makes it important to focus on the critical resource of communication from a control design point of view. Several effects of propagation occurs in the wireless communication due to the using the shared network, such as the variation of uncertain data-rate induced for the network's users. As a result, nonlinear and disturbances that may be stochastically driven occurs making the problem of the WNCS more challenging [81].

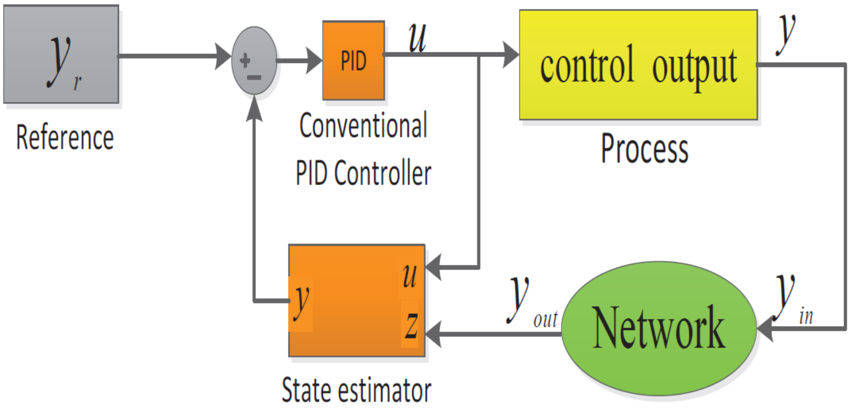

Fig. 6. Regular PID controller with state estimator in WSCS

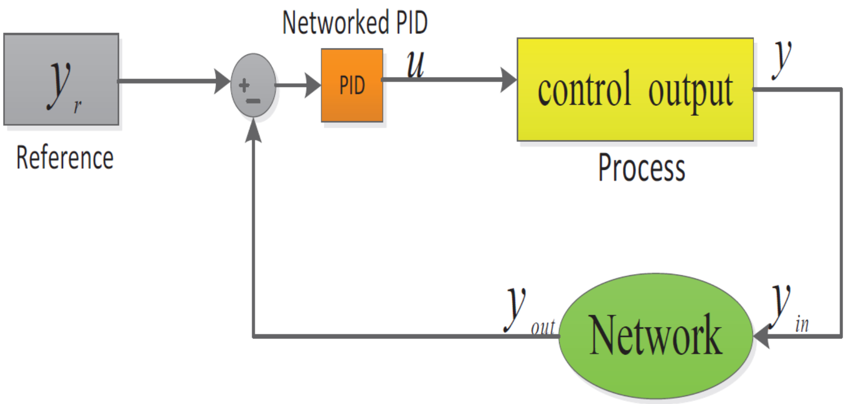

Fig. 7. PID controller with jitter margin tuned in WSCS

There are four main approaches for optimizing the WNCSs:

1. Optimizing the communication infrastructure for a given controller: It means that the radio communication stack is modified, or using of the most costly hardware to stay near the perfect communication. So the behavior could be unsatisfactory because of the hardware limitations. This approach was applied for improving the quality of service (QoS) of the network and achieve the stability of an inverted pendulum/cart system [82].

2. Optimization the control system for a predetermined communication infrastructure: This approach aims to achieve the desired closed loop performance while using the slower and less expensive hardware. Here, the theory of NCS is applied and developed to determine the conditions needed for this objective and pay the attention to the controller analysis and design [81].

3. Codesign approaches: Both of parameters of the control system and the wireless network are optimized together while taking into account the crucial system variables.

4. Interactive design approaches: the wireless network parameters are regulated while considering the constraints of the crucial variables, which is normally affected by the required performance of the controller.

In the following subsections, we present the main approaches in the optimization of WNCSs, i.e. the Co-design approaches and the interactive design approaches.

3.1. Co-design in WNCSs

There exists a trade-off between the quality of service (QoS) in the network and the behavior of the control system, with random access MAC represented as a function of network traffic, i.e., the sampling time applied by the control system. This problem can be solved if the available bandwidth of the network is too low, by the addition of a high-speed backbone network, balancing the load, the expanding the sampling interval, or changing the network topology.

The physical layer in the case of packet dropout requires improvement or acknowledgement and resending. A state-estimator or a control system consider the delay jitter could be implemented on the control side. If packet dropout are caused by collisions or if the retransmission causes delay jitter, the solution will be to use a deterministic MAC protocol, or the controller should be replaced by implementing other approach for compensating the dropout [83, 84, 85].

A structure for the joint design of wireless network and controllers is presented for a WNCS that applied IEEE 802.15.4 protocol for transmitting the signals of the measurements [86]. Both of packet loss and delay of a IEEE 802.15.4 network are considered in the control cost function which is solved using optimal control method. To clarify the applied co-design approach, let us assume a plant i, for $i = 1, \ldots, M$, the follwoing linear stochastic differential equation describe the system

$$dx(t) = Ax(t)dt + Bu(t)dt + dw(t) \tag{7}$$

The following time-varying discrete time system is acquired using ero-order-hold

$$\begin{aligned} x_{k+1} &= \Phi_k x_k + \Gamma_0^k u_k + \Gamma_1^k u_{k-1} + wk \\ y_k &= C x_k + v_k \end{aligned} \tag{8}$$

where $\Phi_k = e^{Ah_k}, \Gamma_0^k = \left[\int_0^{h_k-d_k} e^{As} ds\right] B, \Gamma_1^k = \left[\int_{h_k-d_k}^{h_k} e^{As} ds\right] B$, and v_k is a discrete-time white Gaussian noise with zero mean and variance R_v, and the initial state x_0 is white Gaussian with mean $\bar{x}_0$ and covariance P_0. So, the augmented state space can be described as:

$$\begin{aligned} z_{k+1} &= \Phi_d z_k + \Gamma_d u_k + w_k \\ \hat{y}_k &= \gamma_k y_k \end{aligned} \tag{9}$$

where $\Phi_d = \begin{bmatrix} \Phi & \Gamma_1 \\ 0 & 0 \end{bmatrix}, \Gamma_d = \begin{bmatrix} \Gamma_0 \\ I \end{bmatrix}, C_d = \begin{bmatrix} C & 0 \end{bmatrix}$

Let the the objective function E_{tot} used in the constrained optimization problem that is formulated as follows:

$$\min_{h,V} \; E_{tot}(h, V, \delta) \tag{10}$$

$$\text{s.t. } J(h, p(h, V, \delta), d(h, V, \delta)) \leq J_{req}. \tag{11}$$

The sampling period h and the protocol parameters of the network V are selected as the decision variables in this model. The parameters of the network setup such as number of nodes, length of packet, and a network topology are included in δ. Also, the control cost $J(h, p(h, V, \delta), d(h, V, \delta))$

is the desired maximum control cost, as can be noticed, it is a function of the sampling period h, probability of the packet loss p, the delay d, and J_{req}. More details about the design and the result to this problem could be found in [86].

Several design considerations were addressed to facilitate the deployment of a fully automated closed-loop WNCS for a proposed topology for potential use [87]. The nodes in this topology are assumed to be attached to the sensor and actuator, input and output of the controller, and the intermediate network system. Both of optimal controller and network systems were considered in the design of the optimal controller for this WNCS.

Remark 4 *It should be noted that some components of the network system are not needed for meeting the controllability and observability, and hence the stabilizability and detectability, requirements for the existence of a controller system. These elements can be eliminated since they are not part of the topology. As a result, a simpler design of the network system is obtained which decreases the scale of the closed-loop WNCS* [87].

3.2. Co-Design Approaches for Optimizing WNCSs

In the Co-design approaches, the parameters of the control system and wireless network are optimized together while the tradeoff between their performances are considered. Examples of the designed parameters are, the sampling period, the parameters of the access and algorithm applied, parameters of the duty-cycle, and paths of routing used by the communication channels [3]. Following are the main types of the joint design approaches:

3.2.1 Time-Triggered Approach

The time-triggered approach can be categorized according to the layers of the communication network as follows:

- **Contention-based Access:** The implementation of this protocols needs to consider the probability distribution of packet loss and delay in the model of the wireless network and how it affects the controller part [86, 88].
- **Schedule-based Access:** A framework for the optimization of the communication-control joint is presented to encompass the functional abstraction of the controller as stochastic constraints for the MATI and MAD [1, 89, 90].
- **Routing and Traffic Generation Control:** In this method, the worst scenario of loss of multiple controllers is minimized by using a cross-layer optimized control (CLOC) protocol [91]. Also, CLOC is applied in a network of wireless sensor and actuator including communication using a multihop mesh network. The design method apply a constrained maxmin optimization problem such that the objective function consists of maximizing the minimum redundancy exists in the network, while the stability of the controllers and the ability of the communication system to be scheduled, are considered to be the constraints in this problem [92, 93].

3.2.2 Event-Triggered Sampling

The design of the communication system for the sampling in event triggering mainly considers the MAC layer. The Event-triggered approach can be categorized as follows:

- **Contention-based Access:** Many literature consider and analyze the compromising between the packet losses occur in the communication network and the level threshold crossings occur in the controller [94, 95, 96, 97, 98]. In [94] for example, the control system using event triggering approach is discussed in lossy communication system. A Bernoulli distribution independent is used to describe the the packet losses occur in each channel.

- **Self-triggered Control and Mixed Approach:** In this approach, the consumption of energy is reduced and contention delay is reduced by estimating the future's level crossings [99, 100].

3.3. Interactive Design Approaches for Optimizing WNCSs

The idea of the interactive design approaches is to tune the parameters of the wireless network to achieve the objectives of the control system. Most of these approaches are based on the time-triggering control systems, in which, the signals are transmitted from the sensors with specific rates. In general, the needs of the controller are assumed to be available as an upper bounds of the fixed sampling period dropout or the packet delay.

Considering the real-time requirement is very important than other performance metrics in WNCSs. keep in the mind that, the real-time performance affected highly by the packet delay and dropout in wireless communication. So, the consideration of the the deadline-constrained MAC protocols of IEEE 802.15.4 and IEEE 802.11 is very essential. The previous research focus on the protocol applied and scheduling rather than the parameters of the physical layer [3].

In the following parts, we highlights the main methods of the interactive design approaches.

3.3.1 Medium Access Control

The literature on the real-time networks of 802.15.4 and 802.11 have two main types as follows:

- **Contention-based Access:** The objective of this random access protocol is the tuning of the parameters of the CSMA/CA mechanism to enhance packet delay, probability of the droput, and the consumption of energy for the controller.

  The energy consumption, delay, and reliability are derived as with respect to the parameters using A Markov model at each node for IEEE 802.15.4 [101]. A deadline constrained MAC protocol with QoS is proposed for soft realtime NCSs by implementing IEEE 802.11 [102]. In [103], experimental measures and the analysis of 802.11g/e network is provided to achieve a better understand of the statistical distribution of the delay in industry that requires real-time communication.

- **Schedule-based Access:** The constraints on the reliability of the nodes and the strict delay can be met by schedule the transmissions explicitly such that the nodes with tighter constraint have the highest priority. A number of several mechanisms of IEEE 802.11 was combined for supporting applications of the soft real-time industry [104]. A real-time wireless communication protocol named RTWiFi, was proposed for supporting high-speed controller with sampling rate equal or higher than 1KHz [105]. A method using TDMA with 802.11 CSMA was implemented by a middleware such that slots with specific time are connected with every real-time node to transmit the signals [106]. In [107], a real-time communication architecture was applied using 802.11 standard.

- **Physical Layer Extension:** An algorithm to schedule the communication while considering the priority in terms of the deadlines of the transmission and sampling periods was presented such that a maximum level of adaptivity is provided [12, 89]. This schedule withstand in the presence of the packet dropouts of the nodes used for time triggering and the nodes of event triggering. In [108], the reliability and time of service of IEEE 802.11n was analyzed for communication applied in industry.

3.3.2 Network Resource Schedule

The slot of time and the link of multihop networks are assigned efficiently using several scheduling algorithms, this helps meeting the strict requirements of delay and reliability, following are the main categories of these algorithms.

- **Scheduling Algorithm:** Some of the scheduling algorithms concentrate on satisfying a common deadline defined used by all packets created within a sampling time [109, 110, 111]. The minimum delay was formulated for the packet communication between common access points and sensor nodes [109]. Novel methods for providing reliability when packet failures occurs was introduced [111, 110]. In [110], the repetition of the most suitable slot was used for building an optimal schedule increment strategy. While in [111], a aster scheduling algorithm is designed.
- **Robustness Enhancement:** The incorporation of different mechanisms of retransmission is allowed at random time instants, due to the predetermined behavior of schedule-based transmissions. And, the failure in the transmission could be occurred as a result of external interference and multipath fading in difficult environments. Some mechanisms based on retransmission are applied at the link layer [112, 113, 114]. The communications can be reduced to minimum by taking advantage of the determinism in the packet headers because schedule is predetermined in the network by the nodes. This strategy help in recovering the unknown bytes of the header [112]. The bits' number in the retransmissions is minimized by using various efficient methods such as symbol decoding confidence [113] and using of the transmitted signal strength variations for determining failure packets [114].

3.3.3 Network Routing

The reliability of the network and the efficiency of the energy in wireless networks has been improved by developing efficient multipath routing. Following are the main kinds of the multipath routings according to the the operation and the routing metric:

- **Disjoint Path Routing:** Including two kinds [115, 116]:
  1. Node-disjoint paths: No relay node used in common.
  2. Link-disjoint paths: No common link used but it could use common nodes.
- **Graph Routing:** Achieve significant enhancement in every single path with regard to the reliability of the worst-case, because of using of multiple paths [117, 118].
- **Controlled Flooding:** Applied in situation that is more strict specifications on the reliability of the routing in harsh and noisy environments [119, 120].
- **Energy/QoS-aware Routing:** In this type, both of the energy consumption by the network and the application specifications are considered [121, 122]

3.4. Summary of Related Research Work

It is a challenging problem to design a WNCS that requires a consideration of both of the control system and the wireless network. Many issues related application of WNCSs in industry were discussed in [123], such as dropout, delay, transceiver operation mode, signal path loss, energy supply, authentication, and security. Several standards are applied in WNCSs including IEEE 802.15.1/Bluetoot, IEEE 802.15.4/ZigBee, and IEEE802.11 [124].

The standard IEEE 802.11 is mainly used in WNCSs and it suitable for data rates 1, 2, 11, 54 Mbps.The MAC protocol used in this standard is the CSMA/CA [125]. But, due to the needs of handshaking and the lack of bounded delay, contention based protocols are not suitable for real-time application [126]. The Zigbee on the other hand, is applied for low distance, around 10m, and could be applied in two ways, either QoS with high rates of data or low power consumption with low rates of data. Bluetooth is suitable for low power and low cost application and it offer a high degree of versatility.

There are two main kinds of routing protocols:

- Proactive protocol: It requests to update information in a constant matter and it shares routing tables. However, a huge traffic is produced in the channels [127, 125].
- Reactive protocol: In this strategy, a route is established at the time of transmitting packets. This route is reserved unless the destination becomes unreachable or when there is no need for it. This strategy has less traffic, but there is a delay in transmitting the packets.

The communication and control codesign and co-simulation of WNCS is discussed and solutions are presented for the applications of wireless control systems [128]. Measurements of real industrial radio environments were used for modeling the packet loss and incorporated into the simulator. A scheduling approach of WNCSs is proposed for the automation of a factory by implementing IEEE 802.15.4 protocol [129]. The communication of real-time mixed data for WNCS apply the super frame of IEEE802.15.4. In [130], adaptive control for WLANs is discussed by defining the priority adaptive control with QoS Guarantee (POAC-QG) protocol.

A type of WNCS that consists of a dynamic system to be controlled and a remote control system for a critical applications of IIoT is discussed in [131]. The behavior of the overall controller is considered in a situation when the average cost function is applied such that the fundamental tradeoff between the sensor's and the controller's transmissions.

A robust stability analysis based on model predictive controller (RMPC) technique of solar WNCSs with stochastic dropouts and time delays is discussed [132]. A full state feedback controller is obtained using the Lyapunov functional method and described by the linear matrix inequality (LMI) technique. The solar WNCS is modeled by a Markovian jump discrete-time linear system and the norm of delay is assumed to be bounded.

A constant gain filter is applied for decreasing the complexity of used Kalman filter at the remote side of the control system for a multiple distributed IoT sensors over a wireless communication network with shared common spectrum [133]. A decentralized dynamic scheduling and information was presented for stabilizing the system.

The wireless communication linking the controller with the sensors is affected by a fading and every sensor sends $q_k^i = \delta_k^i C_k^i x_k$ to the control side at a time k on the N_{re} resource blocks. Because control system have a common radio resource block for the sensors, the transmitted value y_k at each time slot k of the control system is obtained by the following equation:

$$y_k = \sum_{i=1}^{N} H_k^i \delta_k^i C_k^i x_k + v_k \tag{12}$$

where H_k^i represent the matrix of the fading in the communication channel, i is the considered sensor, and v_k is the additive complex Gaussian channel noise. In the end, the Lyapunov techniques was applied to obtain the sufficient condition to ensure the stability and the features on the compromising between the average consumption of power and the state estimation [133].

A problem of remote state estimation in the case of several sensors, that observe a dynamic plant is considered, the local state estimates are sent by sensors through a network to a remote estimator

[134]. The network is assumed to be independent and identically distributed (i.i.d.) packet dropout. An optimization problem is applied to obtain the behavior such that it combines the error covariance of the estimation and the consuming of energy by sensors is minimized.

4. Applications of WNCSs

Installing wires over hundreds of meters to be used in a specific application is very costly, unpractical, and decrease the flexibility of the network's layout. While the use of the existing communication networks provide a technological alternative for the otherwise costly application. As a result, the applications of WNCSs are increasing by time and covers a very wide applications. There are a lot of applications reported in the literature. And, in this section, we highlight some of these applications.

WNCSs are discussed in the cooperative control of multi-agent systems, such as robots and vehicles that operating in different places. These applications include autonomous vehicle in a large warehouse with high traffic [135], autonomous soccer's robots [136], autonomous aerial vehicles [137], and cooperative adaptive cruise control of vehicles following each other [138, 139].

Remark 5 *wireless communication among vehicles is the key element to enable the technology for the implementation of cooperative control of multiple agents. As a result, the uncertainty inherent in wireless communication cannot be avoided. This uncertainty lead to a motivating problem in a real-time and safety-critical control application because of the possible producing of unsatisfactory performance or causing collide in the vehicles if not considered in the appropriate way* [81].

One application area of WNCSs is the control system using a shared communication sysem in real time industry. The sensor, controller, and actuator nodes share a common communication medium in this application. It represents the industry of large-scale systems. Some examples of this industry are: wind farms [140], industrial factories [141], water transportation networks [142], and electrical power distribution networks [143].

Other applications of WNCSs are summarized in the following paragraphs.

4.1. Kite Power Systems

Kite power systems (KPSs) are a class of what are called airborne wind energy systems. Similar to wind turbines, KPSs are applied to convert wind energy to electrical energy. But, these kind of systems have more useful than other methods of using massive turbine constructions.

Fig. 8 shows the working principle of a kite power system. A type of KPSs produces the electricity by pulling a tether fixed at a base station [144, 145]. It is required to have a data transformation between the base station and the kite, since the the base station act on the the tether by reeling according to the position and velocity of the kite for generating the power. lllSince the kite far from the base station and due to the strong forces affecting the tether, the wired communication is undesirable or even impossible. So, a wireless control system has to be built to obtain the maximum energy of this system [81].

4.2. Intra-Vehicle Wireless Network

Wireless networks are growing up within vehicles to reduce the cost of both maintenance and manufacturing of the possible needed wires [12, 13]. The harnesses of wiring implemented for communicating signals within the structure of the nowadays vehicle could reach up to 4000 items, with a 40 kg weight and wiring around 4 km. The elimination of the wiring has extra advantage of enhancing the spur innovation, greenhouse gas emission, and the efficiency of the fuel.

The elements of the intra-vehicular WNCS include a controller, wireless sensors and actuators, and a battery. The nodes of the sensors transmit the signals to the controller part and scavenging

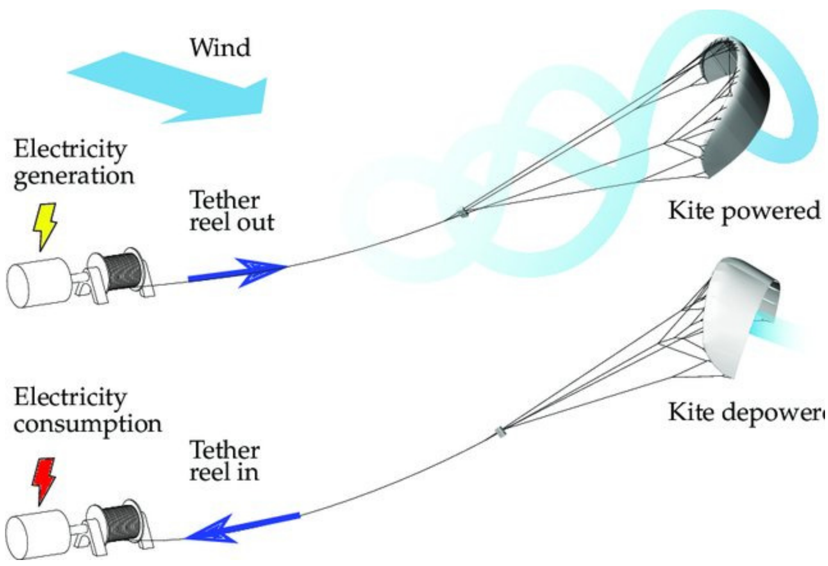

Fig. 8. Working principle of the kite power system

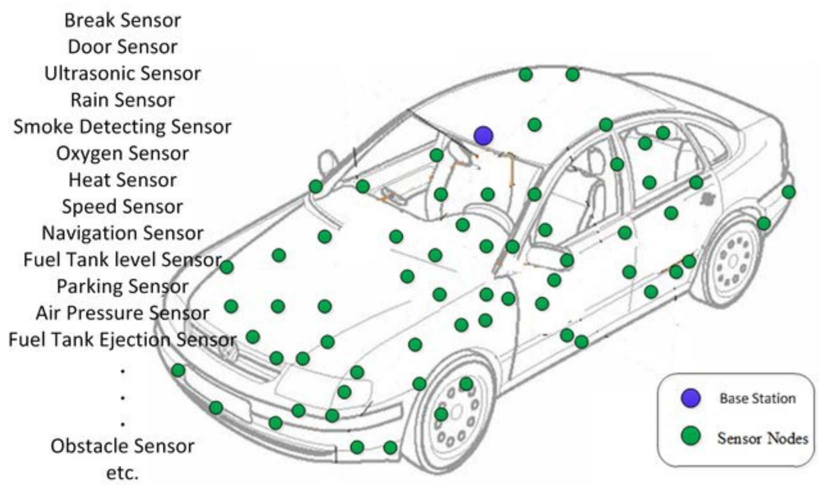

Fig. 9. An example of intra-vehicle wireless network

energy from the corresponding connected devices. The controller sends its commands to the wireless actuators, which receive the power as well from the corresponding scavenging device [81].

The first applications of WNCSs in intra-vehicle systems are Intelligent Tire and Tire Pressure Monitoring System (TPMS). In the Intelligent Tire, wireless sensors are placed inside the tire and used for collecting and sending accelerometer signals. This system help increasing the safety of the vehicles [146]. TPMS on the other hand, focus on sending the pressure signals from the sensors located in the tire to the controller [147].

4.3. Wireless Avionics Intra-Communication

Another recent application of the WNCSs in the growing industrial systems is the Wireless Avionics Intra-Communications (WAICs). It affect improving the performance of aircraft in several ways, such as enhancing the safety, reducing the cost of maintenance, reducing the overall weight, and operating the flight with less cost [11]. Recently, the communication between sensors and the controller is provided by the cable harness, that is also used for controlling the flight [11]. The modern aircraft contains 5000 items or even more, so it require a huge wiring for connecting the corresponding sensors and actuators because of the high requirements of both of the efficiency and the safety. Wiring harness reach up to 2-5% of total weight [148].

The inner and outer wireless sensors of avionics are considered in the WAICs which aims to maintain the structure of the aircraft in a healthy circumstances. Some examples of these sensors are the ice detectors, smoke sensors, landing gear sensors, and engine sensors [81]. The frequency band 4.2-4.4 GHz in the aircraft systems is reserved for the WAICs. So, the WNCSs for the avionics systems is designed according to these limits [11].

4.4. Building Automation

The recent building automation that applied wireless channels show an improvement in decreasing the cost of installation and it allow to define new constructions and a large retrofit market. Building automation aims to minimize the consumption of energy and optimize comfort level of occupant [149]. Moreover, WNCSs in building automation are attached to the several equipments such as thermostats, dampers, heating and cooling components, pumps, and fans. So, it is important a high capability of sensing is required to obtain the desired control of some variables like humidity, pressure, temperature, and flow rates.

According to some resources, buildings consumes 30% of electricity and 43% of water of the total resource consumptions. And it is shown that high percentage of consumers agree to install equipments for energy management if it could save around 30% of the consumption of energy [81].

One of the applications of the WNCSs is the smart building ventilation system [10]. This system consists of wireless sensors, plenums, fans, and the ventilated rooms. The objective of this system is to enhance quality of indoor air, efficiency of ventilation, and thermal comfort, and to minimize the building's consumption of energy.

4.5. Industrial Automation

The application of wireless sensors and actuators in the automation of factories and process control provide a good intelligent infrastructure [9, 150, 151]. The using of WNCSs reduces the cost in the field of industrial automation by 90% in comparison with the wiring systems [152].

The main feature of the industrial automation is the continuous processing control, such as the chemicals, gas, and oil industries. The implementation of WNCSs in these industries will provide the behavior of pumps, vibration levels, ventilation, heating, or fuse. In total, hundreds of sensors and actuators need to communicate with the central unit or other access points [81].

4.6. Water Pumping

The application of control systems in water pumping include the experimental equipments in the laboratories and the production plants. The using of WNCSs in this field will help to maintain the communication with moving parts, vibrations, and chemicals that are located in harsh environments. As a result, it will maintain the control system which could include PLCs and technologies of industrial WLAN, in addition to the wireless sensors, distributed module of the input and output, and the water pump [81].

The communication network is mainly based on Industrial Ethernet in water pumping, while it uses the TCP/IP standard to diagnoses, configures, and parametrize the signals. The PLC is used for transmitting digital signals for controlling the water pump, i.e., turning it on or off. The data required for taking the decision include mainly the level of water in the tank. The implementation of a WNCS will reduces the maintenance and installation cost and increases the flexibility of the structure, while maintain the reliability and robustness of the operation [153].

5. Security Issues in WNCSs

The communication network used for to connecting controllers, actuators, and sensors in WNCSs takes place in a common medium. So, it could be affected by cyber attacks during the communicating of the data. The cyber attacks could cause instability in the system, a physical damage in some parts, or undesired behavior of the system. As a result, discussing the cyber security of WNCSs is a significant issue.

The cyber attacks affecting WNCSs can be categorized as follows [154]:

1. Denial of service (DoS) attacks: It is defined as the strategies applied by the attacker to occupy the resources of communication and aims of preventing the transmission of sensing and controlling signals.
2. Deception attack, In this attack, the invaders modify the signals or the sent packets in some parts of the WNCS.
3. Jamming attacks: This is a special kind of DoS attacks, in which the attacker cause an eradication or diminishing in the capacity of the network by causing a jam at some nodes in the system.
4. Replay attack: This is considered a kind of deception attacks, where the actual data in the network is replaced by a recorded signals saved by the invader.
5. Spoofing attacks: The invader in this kind claims different node by applying faked identity for accessing the communication network. Following will be a DoS attack or a man-in-the-middle attack.

In the following we are summarizing some recent literature to highlight the security issue in WNCSs.

The problem of jamming attacks affecting WSNs is solved using defense method based on swarm intelligent algorithm [155]. This technique is efficient in adapting the modification in the topology of the network and the traffic. Here, the transmitter escape from the jamming by choosing another link for sending the signal, hoping that it is a safe one. On the other hand, the attacker maintain targeting a single channel with a hope of disrupting any fragment could be sent in the pulse jamming method. Finally, the ants select the next hop in a random way when the data of the channel is available.

In [156], a system is proposed to detect and avoid intrusion in WSNs. A game theory method with an algorithm based on fuzzy Q-learning is applied to optimize the players' policies [157, 158]. A defense strategy is designed to avoid DDoS attacks in the application layer, by coordinating the base station and sink nodes in a three-player game. The three players in this game are the attacker, a base station, and sink nodes. The defense method consists of detection and defense parts. If the invader inject flooding signals to a specific node that exceeds a predetermined threshold, the game begins. The behavior of the presented approach is reviewed and compared with other methods by applying a prominent WSN protocol, that is the low energy adaptive clustering hierarchy [159]. The find outs are this approach is efficient and shows accurate detection, less using of energy, better network lifetime [160].

In [161], the strategy Dos attack for maximizing the LOG cost function with constraints on the energy was studied by the attacker. The estimate of the state is calculated at the side of the sensor. So, the wireless network channel is used for sending the value of the state estimation and the covariance of the error to the side of the remote estimator. This behavior causes a high pressure of network bandwidth and requires the implementation of smart sensors. A necessary and sufficient conditions for a problem of undetectable attacks in system consists of multi-sensors is presented in [162].

In [163], a model of multivariate evaluation is established to find the suitable number of sensors. A cooperative game is applied in designing a strategy for power allocation in an optimal way in the presence of multiple attackers [164]. A probabilistic attack approach is proposed for a problem of perceiving the channel state by the attacker [165]. In this attack, it is assumed that the DoS attack is excuted only if the channel is idle.

Optimal attack schedule problems are investigated for the wireless CPSs with DoS attack affecting two sensors [166]. But, the variation in the time allocated for the attack on each sensor and the "universality" of the attack were not considered in the solution. A jamming attack system is established for a type of a WNCS targeting each sensor in the system [167]. A few major security attacks on the intelligent connected vehicles is identified [168]. A comprehensive survey of available defences against these attacks is discussed on intelligent vehicle systems.

6. Conclusion and Future Work

A wireless networked control system (WNCS) consists of a dynamic system to be controlled, sensors, actuators, and a remote controller. A WNCS has two types of wireless transmissions, i.e., the sensor's measurement transmission to the controller and the controller's command transmission to the actuator. In this paper, we are surveying the literature on the communication networks in WNCSs and the challenges related to them such as the communication standards, delay, Packet dropout, and delay jitter. Then, the control approaches in the design of a WNCS are presented including the interactive design approaches and the joint design approaches. Also, several applications of WNCSs have been discussed in terms of its structure, functionality, and control design. These applications include: Intra-Vehicle Wireless Network, Wireless Avionics Intra-Communication, Building Automation, and Water pumping. After that, security issues in WNCSs from a control engineering point of view are detailed while focusing on the major kinds of cyber attacks affecting WNCSs. Finally, future directions and conclusions are summarized in the end of the paper.

Given the specific application domains mentioned above, being able to analyze and design WNCSs, thereby guaranteeing their reliability, may lead to a significant societal impact including the benefits of relieving traffic congestion on highways, cheaper and more environmentally friendly energy-harvesting systems, and efficient regulation of city-wide systems that are vital to modern society. To obtain these benefits, the theory developed by the WNCSs community must be delivered in the form of user friendly design/analysis tools to the control engineers who ultimately design and implement control strategies and define network requirements to meet certain closed-loop stability, performance, and reliability specifications.

Future work could be carried out also along the following directions:

- The master-slave method for remotely controlling WNCSs seems to be a productive research direction. One should further pursue investigations into the issues of synchronization of the time clocks, the structure of the master and the slave, control data processing, and real-time implementations.
- The industrial automation area deserves collaborative work to build and experiment with robust WNCSs while implementing cloud computing and intelligent control methods.
- The class of model-predictive control methods deserves additional for WNCSs with particular emphasis on industrial applications.

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