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A Compensation Model for Packet Loss Using Kalman Filter in Wireless Network Control Systems

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Abstract: In Wireless Network Control System (WNCS), a study approach is relevant for the development and analysis of control strategies that provide the operation of dynamic systems. Among the real characteristics of the communication channels, a packet loss is one of the main deficiencies present in the transmission of data in a wireless network. For a dynamic system in the presence of losses, a filtering technique makes it possible to estimate system states using process output measurements and to mitigate a performance drop. It is important to study packet losses in Wireless Network Control Systems because packet loss can severely degrade the network performance. Wireless networks are particularly vulnerable to packet loss due to factors such as interference, fading and signal attenuation. The present work analyzed the behavior of a real WNCS plant at different levels of packet loss using the IEEE 802.15.4 protocol. Also, we propose a compensation model for packet loss using the Kalman filter. The packet loss process is based on a Gilbert-Elliot model and is compared with a Proportional-Integral-Derivative (PID) controller. The results show that by applying Kalman filters it is possible to improve the operation of the process in case of losses during data transmission. It was observed through the simulation that it is possible to reduce the error of the system output in relation to the reference in the presence of packet loss. For a loss ratio of 30%, the observed improvement in the system behavior with the use of the Kalman filter was 26.1%.

Keywords: control mesh; packet loss; system control network; WNCS; Kalman filter

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1. Introduction

The industry has been studying and exploring the use of wired and wireless technology in various areas, including monitoring, automation and control. The primary advantage of using wireless technology is the lower installation cost, both in terms of finances and labor effort, as well as increased flexibility in device distribution, such as sensors and actuators [1]. As a result, new technologies like Wireless Sensor Networks (WSNs) have gained global attention [2–4], especially with the proliferation of Micro-Electro-Mechanical System technologies, which has facilitated the development of intelligent sensors [5].

Industrial environments are major users of wireless technologies, and their use presents significant challenges due to the high quality requirements expected in these networks. Factors such as latency and ambient noise can impact the performance of a Wireless Sensor Network (WSN) [6]. These issues, among others, are prevalent in automation systems due to the growing complexity of industrial plants. In this context, Networked Control Systems (NCS) have gained considerable attention [7,8], including efforts to prevent attacks on these networks [9]. In industrial networks where the controller and plant are physically separated, the elements are connected through a communication network to close the control loop, giving rise to the NCS concept [10]. Figure 1a shows a simple closed-loop system. In closed-loop control systems, signals are transmitted between the cascading elements, allowing the system to continually use the communication network for new transmissions. This mechanism is called multiple-loop, improves system linearization and reduces the impact of noise. However, NCS problems inherent in control applications can be difficult to detect and identify due to the variations and uncertainties introduced by the communication network, such as delay, packet loss, interference, bandwidth and instabilities [11].

According to [12], NCS have several key issues that directly impact system stability. These include bandwidth limitations due to synchronous data communication, sampling and delays, where the information must be sampled, digitally encoded, transmitted and decoded; which may cause network delays and packet loss during transmission, usually at the physical layer or due to lack of memory (buffer overflow) caused by congestion. These problems can significantly impact the performance of the control mesh, and may even render it unstable or inoperable.

The development of wireless technologies such as IEEE 802.11 (WLAN, Wireless Local Area Network) [13], IEEE 802.15 (WPAN, Wireless Personal Area Network) and IEEE 802.16 (WMAN, Wireless Metropolitan Area Network) have expanded the use of these technologies in the industry. Among these communication patterns, the WPAN IEEE 802.15.4 represents an emerging standard for monitoring and controlling NCS networks [14]. The possibility of using wireless networks in NCS and promoting interoperability between networks led to the emergence of Wireless Network Control Systems (WNCS) [15–17], as shown in Figure 1b.

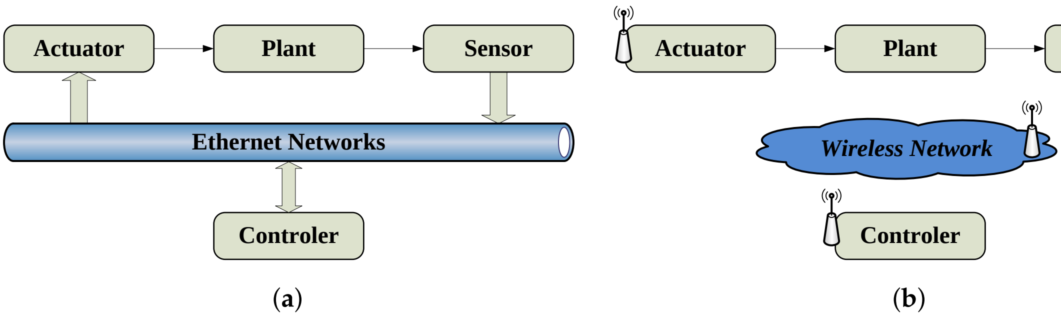

Figure 1. (**a**) Representation of a NCS and (**b**) Representation of a WNCS.

However, as wireless sensor networks and network control systems continue to expand, the challenges of obtaining more reliable and efficient control systems increase considerably. For the development of more reliable systems, a multidisciplinary approach is needed in NCS/WNCS, including communication network technologies, signal processing and dynamical system control theory; so that a system can be remotely controlled with the reliability of a dynamic system [18,19]. In WNCS, packet loss is one of the most common factors that decrease the stability of the control system [20,21].

Due to the multidisciplinary approach in WNCS, simulations of network control systems play an important role in the stages of development and analysis of controller performance. Control and management in WNCS networks not only allow the development of a new variety of control systems but also enable better estimation of new parameters. In the current literature, the use of different techniques in network control systems has allowed rapid growth in WNCS. To assist in this development, the use of filters has gained great interest. For a dynamic system in the presence of packet loss during transmission, the purpose of the filter is to estimate the states of the system using noise output data measurements. The use of Kalman filters allows the use of recursive algorithms to minimize the variation of this error [22]. WNCS instability increases the challenges for better systems. For this reason, there is a need for accurate models for transmission channels and analysis of controllers to mitigate the effects of packet loss [23].

To improve the modeling of WNCS, it is essential to collect reliable data that represents real environments. The real characteristics of communication channels, such as packet loss are generally not used to develop reliable control models, thus highlighting a significant research gap [24].

In WNCS, packet loss can cause delays, errors and loss of control, which is especially problematic in critical applications such as industrial automation, healthcare and transportation. To improve reliability and performance, researchers and engineers study packet losses and develop methods to compensate for them, such as error correction, retransmission and prediction using Kalman filter, for example. Physical layer improvements can also reduce the likelihood of packet loss.

In this paper, a new prediction model based on Kalman filter is presented, aiming to analyze the behavior of the process when packet loss occurs. The results were collected from a closed-loop control plant using IEEE 802.15.4 wireless communication. The use of this protocol was based on previous studies in [25,26]. The Gilbert-Elliot model was used to simulate packet loss process. This paper presents two main contributions: first, the performance analysis of the Gilbert-Elliot model for modeling packet loss from a real control plant, where the calibration parameters of the model were obtained as a function of the loss ratio for the evaluation of WNCS; second, the application of the Kalman filter to obtain the reduction of the error associated with the operating behavior of the plant when failures occur during transmission due to packet loss. The comparison between non-compensated and compensated behavior was performed using two metrics: RMSE (Root Mean Square Error) and R^2, which evaluate the performance of the feedback system.

The remainder of this paper is organized as follows: Section 2 presents the main related works. Section 3 describes the scenario test-bed and the proposed method. The main results are presented in Section 4. Finally, some concluding thoughts are summarized in Section 5.

2. Related Works

This section presents a brief overview of packet loss in wireless systems and the main papers developed for controlling systems using WNCS. Packet loss may be understood as a packet that is sent over the network but is not correctly received by the receiver. During transmission, this loss can occur for several reasons in the Physical (PHY) or Medium Access Control (MAC) layers [27]. Determining the causes of packet loss is important, as it allows for a better description and estimation of the model that represents this behavior. Packet loss in a wireless network can be divided into three categories: losses resulting from low signal strength (RSS), losses resulting from collisions caused by multiple transmitters using the same transmission channel and losses resulting from collisions caused by asynchronous transmissions, which is caused by hidden terminals [27]. It is observed that other parameters are also important for understanding these losses, such as low signal power levels, physical obstacles causing signal fading, noise, competition in the channel causing collisions or loss of memory buffers in transmitters, access points and receivers [28].

The authors in [20] analyzed the performance of a WCNS that used an alternative PID controller under packet loss conditions. They also studied a predictive PI controller (PPI), based on delay data and end-of-course processes. The PPI allows for model compatibility, maintains the PID simplicity in terms of adjustable parameters and produces an improved performance in terms of system overshoot, rising time and absolute integral error [29].

The application of H_∞ filters as controllers are applied in WNCS in low bandwidth [30] or in investigations of the problems by using the same filter in closed-loop systems [31]. The application of stochastic networks based on delay and packet loss is used in the development of linear controllers in closed-loop plants from the use of wireless networks [32]. In many wireless systems, the real-time control of tasks is performed through scheduling algorithms that prioritize the tasks of collecting and managing the transmitted data [33].

Also in closed-loop systems, system topologies based on Linear Matrix Inequality (LMI) algorithms for an optimal controller and wireless network systems are applied while network performance is measured. This approach assists the controller in the stabilization of the closed-loop system and provides the means to connect the sensors and actuators of the plant to the inputs and outputs of the controller [34]. Furthermore, the investigation of predictive controllers in models triggered by events in transmission channels with packet loss [35].

Although a wide range of controller applications for WNCS is observed, the specific use of Kalman filter [36,37] still represents a small number of controllers in wireless networks, but commonly observed in WSN. The main studies are done in Kalman filter modifications to maintain operational normality in the event of interference from other wireless channels [38], estimation of WNCS states to obtain the best coverage area [39] and treatment of intermittent measurements [40]. Also using Kalman filter, the authors in [41] proposed a delay compensation in NCS and [42] examines output feedback control of WNCS where there are separate links between the sensor-to-controller and the controller-to-actuator.

Markov chain presents one of the main packet loss model for wireless networks [27]. The Markov models facilitate better description of losses stochastic sequence. In this sense, the authors in [43] proposed a simple model of packet loss in WNCS over IEEE 802.11b with four-state Markov chain. In [23], it was used a packet loss model based in two-state Bernoulli model over a WNCS. The Bernoulli model was also used for events discrete control in [44], adding a Kalman filter modified in WNCS. The model showed the environment from transmission successful or not of data in a closed-loop communication. For [45], the development of a tolerant losses design for WNCS can be used from probability packet loss process. Different of previous works where packet loss was used, in [46] the delay was used to verify the stability and compensation performance over IEEE 802.11 network. The IEEE 802.11 standard is commonly used for communication, but [47] considers a NCS composed of several control loops that share the same IEEE 802.15.4 network, where was proposed a distributed control strategy to reduce the energy expenditure of the network in terms of the number of transmissions and idle listening periods, but was not analyses a compensation or stability of packet loss. The delay compensation was proposed in [48], and a time-varying Kalman filter was designed for state estimation and feedback control of system.

The paper [49] addressed the issue of state estimation in NCS with lossy network communication, which can lead to inaccuracy or delays in state information. The authors proposed an event-based state estimation method that uses state information only when it is necessary to update the state estimate. This helps reduce the amount of network communication required, which is particularly important in low-bandwidth wireless networks. The paper presents a theoretical analysis of the performance of the proposed method, as well as simulation results that demonstrate its effectiveness compared to other state estimation methods. Also, the authors in [50] addressed the issue of performing Kalman filtering over a packet-dropping network using Round-Robin protocol scheduling. The authors proposed a new Kalman filter structure that can handle the situation where multiple sensors transmit data to a control center over a network that is subject to packet loss. The proposed method utilizes a Round-Robin protocol scheduling scheme to ensure that data from each sensor is transmitted to the control center in a timely manner. The authors also provided an analysis of the stability and performance of the proposed filter. Overall, the papers are relevant to researchers and engineers interested in designing and implementing networked control systems with lossy network communication, providing a promising solution for state estimation in such systems.

Unlike previous studies, this study seeks to quantify the effect of packet loss in a specific plant based on a feedback control system with wireless communication operating under the IEEE 802.15.4 protocol, and evaluate the reduction of this performance degradation with the uso of the Kalman filter. Table 1 shows the simple comparison of the works related to our proposal.

Table 1. Comparative works.

Reference	[51]	[20]	[29]	[30]	[31]	[32]	[33]	[47]	[34]	[35]	[37]	[38]	[39]	[47]	[46]	*
WNCS		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Packet loss parameter	✓	✓		✓	✓	✓				✓	✓	✓				✓
Gilbert-Elliot model																✓
IEEE 802.15.4								✓						✓		✓
Real plant analysis												✓				✓
Simulation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Kalman filter											✓		✓			✓
Compensation error	✓											✓			✓	✓

* Proposed method in this paper.

3. Methodology and Proposed Model

This section describes the scenario in which technical data were collected and presents our proposed model. The setting in which the data were collected provides important contextual information that can help readers better understand the findings and conclusions presented in this paper. Furthermore, presenting the proposed model in this section enables readers to better understand the theoretical framework and approach adopted by the authors. This can help readers to assess the validity and applicability of the proposed model in their own research or practice.

Herefore, after obtaining the plant data through the IEEE 802.15.4 protocol, using the Gilbert-Elliott model and recognizing the packets that formed the behavior of real losses, the behavior of simulated losses was determined and the algorithm was defined to mitigate the effect of losses. In addition, the continuous control system of the plant was converted to a discrete system through the MATLAB platform to evaluate the digital WNCS.

3.1. Sample Collection

Sample collection is a critical process to ensure the accuracy and reliability of the results obtained from the collected samples. Therefore, it is important to perform the collection using appropriate techniques and specific protocols for each type of sample.

The scenario used to collect the behavioral data transmission information is presented in Figure 2. The proposed WNCS consists of a control plant with the objective of controlling the direction of rotation and the speed of a DC motor. The wireless control network follows an end-to-end topology between two XBee Series 1 nodes. Node 1 was parameterized as the controller, and node 2 was parameterized as the sensor. Two Arduino UNO modules were attached to the nodes to process wireless network signals. The measurement of data loss was performed using the data acquisition device IEEE 802.15.4 Packet Sniffer from Texas Instruments [52].

The plant control system was configured and adjusted to maintain the speed of a motor at 2400 RPM (Rotations Per Minute) (Voltage: 12 Vdc, Torque: 198 gf.cm). The Arduino control module is responsible for performing mathematical calculations using the plant data to keep the process working around a specific value (set point). Meanwhile, the Arduino sensor module is responsible for driving the motor and reading the encoder signal (Voltage: 5 Vdc, Resolution: 360 pulses per revolution). Figure 3 shows the test plant, while Figure 4 displays the result of closed-loop control of the process with the influence of packet loss during data transmission.

Considering the scenario and operating configurations of the plant, the nodes were exposed to metric variations in an indoor environment where industrial machines, such as lathes, mechanical milling cutters, and industrial robots, were in operation. The objective was to evaluate the number of lost packages. These variations involved distances, which resulted in an approximate distribution of losses as shown in Table 2. For this analysis, the packages were transmitted at constant intervals of 350 ms, which is the minimum time required for proper plant operation. Each distance was tested with 10 repetitions, and 10,000 packets were sent for each transmission.

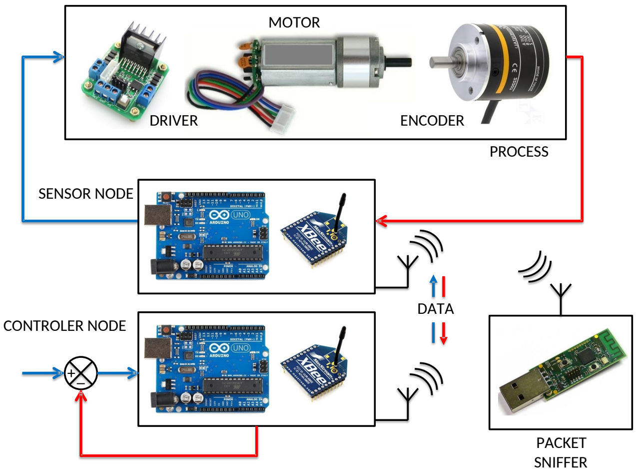

Figure 2. Scenario to perform the tests, in blue the control signal and in red the feedback of the plant.

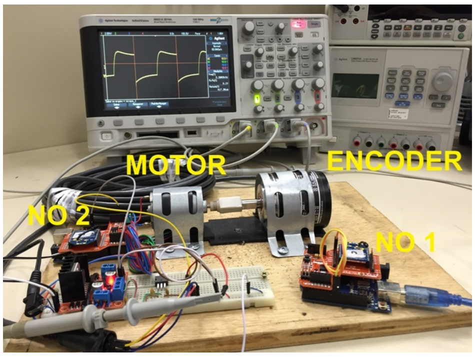

Figure 3. Test plant schematic.

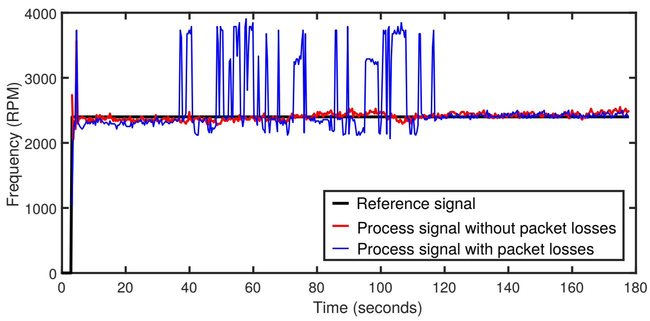

Figure 4. Set point at 2400 RPM.

Table 2. Packet loss to each distance (Distance × Loss Ratio).

Distance (Meters)	Loss Ratio (%)
1	10
3	20
7	30
9	40
13	50

Figure 5 illustrates an example of a transmission captured by the Packet Sniffer, where the first packet contains data sent by the node sensor. These data show that the FCF (Frame Control Field) requests an ACK and the Sequence Number has a value of 0×68 (hexadecimal). Note that in the second, third, and fourth packets, there was a retransmission of the data, and the packet was not received by the controller node, as there was no confirmation of the ACK. In the fifth packet, a new data 0 × 69 was sent and the sixth packet consists of an ACK from the previous packet, as it has the same Sequence Number and a value of zero in the FCF. The analysis shows that the 0 × 69 packet was successfully received by the controller node.

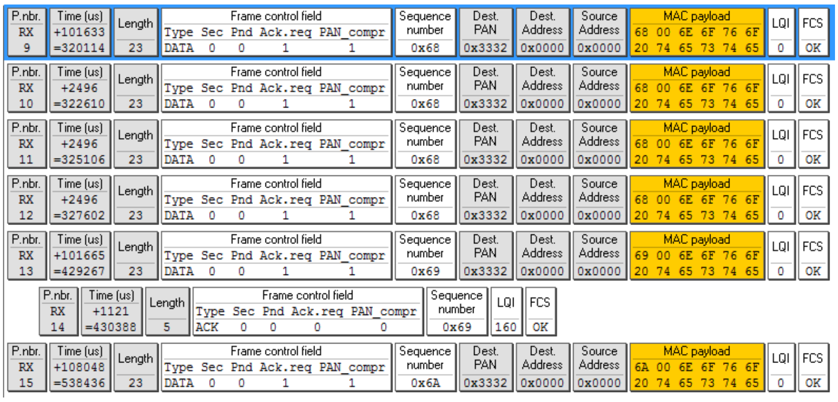

Figure 5. Data analysis by Packet Sniffer.

The data obtained from Packet Sniffer, which included information on successfully received and lost packets, was used to calibrate the Gilbert-Elliot model. This model uses a two-state Markov chain, consisting of the states *Good* and *Bad*, with small and large loss probabilities, respectively [27]. The Gilbert-Elliot model is frequently employed to provide a packet loss model in wireless networks since it can capture the bursty and correlated nature of packet loss commonly observed in such networks. This model characterizes packet loss as being in either a good state (with a low probability of packet loss) or a bad state (with a high probability of packet loss). The transition between these two states is probabilistic and can be influenced by various network conditions such as interference, congestion or fading.

The Gilbert-Elliot model is particularly effective in wireless networks because it can capture the temporal dependencies of packet losses, which are often caused by fading or interference. This model has been demonstrated to provide an accurate representation of packet loss in various wireless networks, including cellular networks, wireless local area networks (WLANs) and ad hoc networks. Furthermore, the Gilbert-Elliot model is relatively simple and computationally efficient, making it an attractive option for modeling packet loss in real-time applications. It also allows for easy parameterization based on measurements of actual packet loss data in a given network. In summary, the Gilbert-Elliot model is utilized to provide a packet loss model in wireless networks due to its ability to capture the bursty and correlated nature of packet loss, its computational efficiency and its ability to model temporal dependencies of packet loss.

These states of Gilbert-Elliot model mean if one packet is received or not, respectively for good and bad states. The 2-state model is shown in Figure 6, where p and r are respectively the transition probability from the good to bad and bad to the good state.

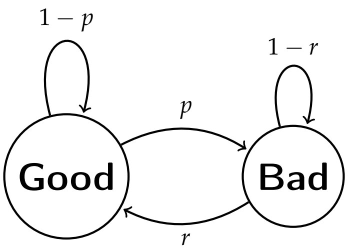

Figure 6. Gilbert-Elliott model 2-states.

The probability of remaining in the same state is given by $1-p$ and $1-r$. In that series with actual state X_t of a stochastic process depends only the state X_{t-1}. The parameters p

e q are used to determine the probability the transition between states of temporal series X_t. The Equation (1) presents the parameter p as the transition probability of good to bad state, while the Equation (2) presents the parameter q as the transition probability of bad to good state.

$$p = P(X_t = 0 \mid X_{t-1} = 1) \tag{1}$$

$$q = P(X_t = 1 \mid X_{t-1} = 0) \tag{2}$$

The state stationarity probability for good and bad states can be calculate from the Equations $\hat{p} = \frac{q}{p+q}$ and $\hat{q} = \frac{p}{p+q}$, and the error ratio can be expressed by the Equation (3).

$$error = (1-k)\hat{p} + (1-h)\hat{q} \tag{3}$$

The Gilbert-Elliot model was applied for each packet loss ratio showed in the Table 2, and allows us to obtain the simulation proceeding of losses in burst. The estimate parameters for $\hat{p}$ and $\hat{q}$ are presented in Table 3.

Table 3. Average calibrated values for $\hat{p}$ and $\hat{q}$.

Packet Loss (%)	$\hat{p}$	$\hat{q}$
10%	0.79	0.08
20%	0.55	0.14
30%	0.40	0.17
40%	0.37	0.23
50%	0.36	0.37

3.2. Compensation Model

Based on transmission information obtained via the Packet Sniffer, the Algorithm 1 was developed for reading and processing the data using the MATLAB platform. This algorithm was used to obtain the actual behavior model of the transmission, which consists of a vector of 0 s and 1 s, where 0 represents a lost packet and 1 represents a successfully transmitted and received packet. In the implementation of the algorithm, the output value of the plant is compared with the transmitted data vector from the sensor node to the controller node at each sampling period. If any packet are lost during transmission, the system will take action to try to avoid a failure in the process operation.

The algorithm used to mitigate the effect of packet loss was assembled using the Kalman filter, which utilizes a series of observed measures over time to estimate potential values for a given system. Figure 7 shows the methodology used to check for packet loss during process operation. It is observed that when there is no package loss, the last output value of the plant will feed the mesh. However, when the packet is lost, the value that will feed the mesh will be given by the prediction obtained by the Kalman filter. The update of prediction values already occurs through observation of the output signal of the plant.

Equations (4)–(6) were used to estimate values from the plant operating behavior. Where $\hat{x}_k$ is the estimated value for the current state, based on the value of the previous state $\hat{x}_{k-1}$, the current observance value z_k (plant output signal) and the current gain value g_k. The value of the Kalman gain is based on the mean value of observation noise r, and on the value of the prediction error p_k. The prediction error in turn is computed recursively.

$$g_k = p_{k-1}/(p_{k-1} + r) \tag{4}$$

$$\hat{x}_k = \hat{x}_{k-1} + g_k(z_k - \hat{x}_{k-1}) \tag{5}$$

$$p_k = (1 - g_k)p_{k-1} \tag{6}$$

The Algorithm 1 presents the working process of the Kalman filter for estimating the values of p_k.

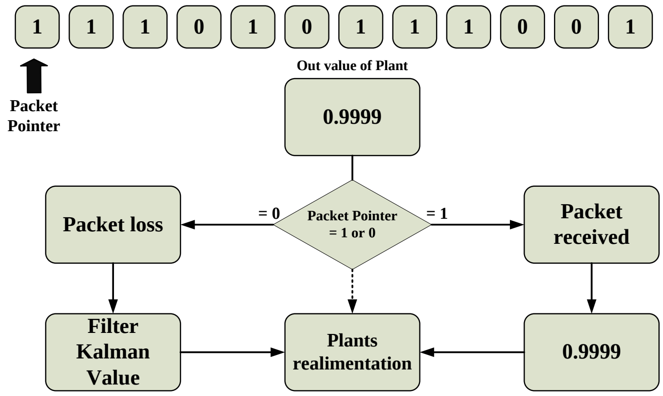

Figure 7. Method to analyse packet loss used on WCNS simulation.

Algorithm 1 Kalman filter applied.

Input: *Packet Pointer*, z_k

1: $k \leftarrow 1$; $\hat{x}_{k-1} \leftarrow 0$; $p_{k-1} \leftarrow 1$; $r \leftarrow 0.1$
2: **for** $k \leq 10,000$ **do**
3: ; compute g_k using Equation (4)
4: **if** *Packet Pointer* $= 1$ **then**
5: $\hat{x}_k \leftarrow z_k$
6: **else**
7: ; compute $\hat{x}_k$ using Equation (5)
8: **end if**
9: ; compute p_k using Equation (6)
10: $\hat{x}_{k-1} \leftarrow \hat{x}_k$
11: $p_{k-1} \leftarrow p_k$
12: **end for**

Output: p_k

It is worth noting that the calculation of the Kalman filter gain is performed using a combination of the mathematical model of the system, the available measurements, and the estimates of previous states. The gain is updated at each measurement cycle and calculated to minimize the mean squared error between the estimated state of the system and the actual measurement. The formula for calculating the gain is given by the Riccati equation, which is a nonlinear matrix equation that describes the uncertainty in the state estimate of the system and the covariance matrix of the estimation error [53]. The process of adjusting the Kalman filter gains is an optimization problem that seeks to find the optimal set of gains that minimize the mean squared error between the estimated state of the system and the actual measurements.

4. Simulation Results

To simulate the operation of the controlled process and analyze the consistency of the data packets transmitted and received between the devices in the network, the control plant was parameterized using Simulink with a discrete Proportional-Integral-Derivative (PID) controller. The second-order control loop is shown in Figure 8.

The transfer function of the closed control loop was obtained by applying a step signal and analyzing the system characteristics, such as overshoot, peak time and settling time. The transfer function $G(z)$ can be seen in Equation (7), where k represents the gain, ζ represents the damping coefficient, and ω_n represents the natural frequency of the system.

$$G(z) = \frac{k}{z^2 + 2\zeta\omega_n + \omega_n^2} \tag{7}$$

The gains of the PID controller for the process were calculated using the root locus method. For the calculation, a 20% overshoot and a settling time of 2.1 s were targeted. The plant in operation without packet loss is presented in Figure 9, where a sequence of step signals was introduced to observe the behavior of the system. The purpose of the control is to regulate the direction of rotation and speed of the motor.

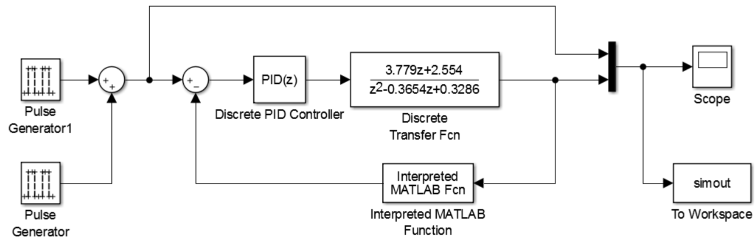

Figure 8. Plant used in the WCNS simulation with sampling period of 350 ms.

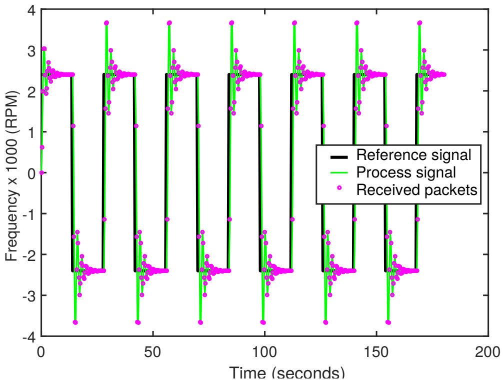

Figure 9. Operation of the process without loss of packets.

As there is no packet loss, the latest output value of the plant will be fed into the control loop, where the Kalman filter is not utilized in this case. Two metrics were employed to analyze the system performance. The first metric is the Root Mean Square Error ($RMSE$), which is calculated as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - r_i)^2} \tag{8}$$

where N is the number of samples, y_i is the observed value, and r_i represents the modeled values. The $RMSE$ is a measure of the average magnitude of the estimation errors, always has a positive value, and the closer it is to zero, the higher the quality of the measured or estimated values.

The first analysis is presented in Figure 10, where the performance of the Gilbert-Elliott model was compared to the real case of packet losses. It is observed that the $RMSE$ of the Gilbert-Elliott model ($RMSE_G$) is close to the actual $RMSE$ of packet losses ($RMSE_P$). In this analysis, 10 measurements were performed with 10,000 packets each, and the standard deviation for each measurement was calculated. The mean $RMSE$ with a 95% confidence interval was plotted.

Another metric used in the system performance analysis was the coefficient of determination R^2, which is calculated as follows:

$$R^2 = 1 - \left(\frac{n-1}{n-p}\right)\frac{SSE}{SST} \tag{9}$$

where SSE is the sum of squared errors, SST is the total sum of squares, n is the number of observations in the series, and p is the number of regression coefficients.

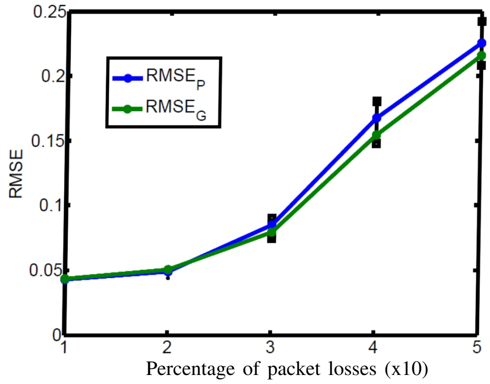

Figure 10. *RMSE* relation with of the ratio of losses.

To present the next results, two scenarios were used. In the first scenario, the data trace from the real plant was used as input to the Kalman filter without adjusting the parameters in the Gilbert-Elliot model. In the second scenario, the parameters from the Gilbert-Elliot model were used.

4.1. Without Gilbert-Elliot

The following are the results of the WNCS analysis with a sampling period of 350 ms. In the process operation without losses, the calculated *RMSE* is 0.9942 and R^2 is 0.8361. Figure 11 shows the behavior of the WNCS output for a packet loss rate of 30% (7 m distance between the network nodes), which was measured by real losses behavior. In this analysis, the system *RMSE* is 1.2654 and R^2 is 0.7643. Note that when compared to the operation without losses, the behavior regarding the controller is 21.4% worse in terms of the *RMSE*.

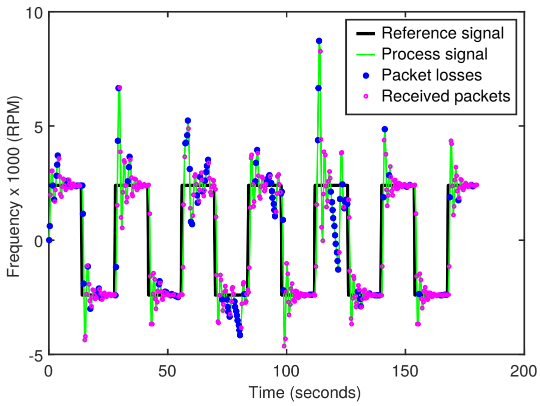

Figure 11. Unstable process operation (compromised) with 30% of packet loss.

To estimate values to be fed to the plant in case of losses, the process was subjected to a package analysis, as shown in Figure 7. From this condition, output values from the plant were extracted and stored in memory. Figure 12 shows the system recovery by applying the Kalman filter, where even though packets were lost during transmission, it was possible to keep the process running according to the actual behavior of the system. In this analysis, the observed *RMSE* was 1.1024 and R^2 was 0.7997.

Table 4 presents the results of the analysis of transmission errors in relation to the percentage of losses. It is observed that the higher the rate of losses, the greater the error associated with the operational behavior of the plant. However, it was possible to achieve a significant improvement in this error with the introduction of the Kalman filter. For example, when comparing the *RMSE* values considering a packet loss rate of 30%, it is observed that an improvement of 11.6% is obtained with the application of the Kalman filter.

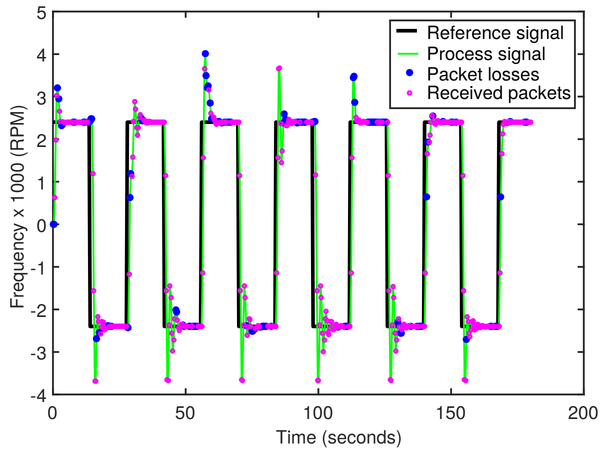

Figure 12. Operation of the recovered process after the analysis of the lost packets.

Table 4. Process errors as a function of packet loss ratio.

Metric	0%	10%	20%	30%
RMSE (without Kalman)	0.9942	1.006	1.0649	1.2654
RMSE (with Kalman)	0.9942	1.0167	0.9915	1.1024
R^2 (without Kalman)	0.8361	0.8339	0.8177	0.7643
R^2 (with Kalman)	0.8361	0.8290	0.8371	0.7997

4.2. With Gilbert-Elliot

For the process in operation without losses, the calculated *RMSE* is 0.9942, and the R^2 value is 0.8361. Figure 13 shows the behavior of the WNCS output signal with a packet loss rate of 30%, characterized using the Gilbert-Elliott model. In this analysis, the *RMSE* of the system is 1.6192, and the R^2 value is 0.6818. Note that when compared to the *RMSE*, the controller performance is 38.6% worse than lossless behavior.

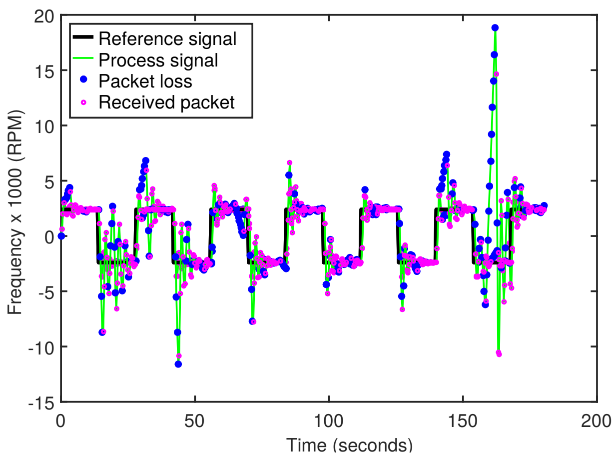

Figure 13. Unstable process operation with 30% of packet loss.

To estimate values that will feed back the plant in case of losses, the process was submitted to data vector analysis, as described in the previous section. Figure 14 shows the operation of the process with the application of the Kalman filter. It is noticed that even if packets are lost during transmission, it is possible to keep the process running closer to the actual behavior of the system. In this analysis, the *RMSE* of the system was 1.1364 and the R^2 was 0.7882. That is, it was possible to obtain a 26.1% improvement in system operation with the Kalman filter.

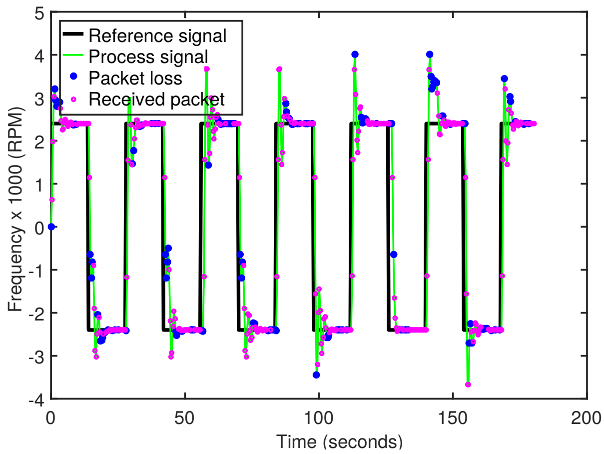

Figure 14. Functioning of the recovered process after the analysis of the lost packets.

5. Conclusions

In this paper, a behavioral analysis of a wireless network based control system (WNCS) was presented, including packet loss measurements using the IEEE 802.15.4 protocol. Furthermore, the loss model proposed by Gilbert-Elliott was applied to a real trace of loss in bursts, presenting an error percentage lower than 6%. It is known that the communication between the nodes of a wireless network is directly related to the distance and, at some point, there may be packet loss during transmission. Therefore, this work sought to mitigate the effect of data transmission losses through the application of the Kalman filter algorithm, in order to minimize the impact on the operation of a WNCS. For a packet loss rate of 30%, the observed improvement in the system behavior with the use of the Kalman filter was 26.1%. This result shows that knowing the real behavior of the plant, it was observed through the simulation that it is possible to reduce the error of the system output in relation to the reference in the presence of packet loss. For comparison purposes, this work also considered the packet loss analysis in the WNCS without the application of the Gilbert-Elliott model. In this test scenario, the simulation results showed an improvement of 11.6% with the application of the Kalman filter, considering a packet loss rate of 30%.

As a future research direction, it is intended to test the Kalman filter in the proposed real plant to evaluate the practical performance of the WNCS. Moreover, for future work, it is suggested to carry out a study to adjust the model to consider packet loss from hidden terminals and/or collision probability caused by a high channel occupancy. It is also observed the possibility of applying other packet loss models, such as the Bernoulli model. Additionally, the use of the Kalman Filter Forward Error Correction (FEC) schema to improve the bit error correction process is suggested as the next step of this work.

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References

1. Mahmoud, M.S. Wireless networked control system design: An overview. In Proceedings of the 2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE), Istanbul, Turkey, 1–4 June 2014; pp. 2335–2340. [CrossRef]
2. Hung, C.W.; Zhuang, Y.D.; Lee, C.H.; Wang, C.C.; Yang, H.H. Transmission Power Control in Wireless Sensor Networks Using Fuzzy Adaptive Data Rate. *Sensors* **2022**, *22*, 9963. [CrossRef] [PubMed]

3. Dhabliya, D.; Soundararajan, R.; Selvarasu, P.; Balasubramaniam, M.S.; Rajawat, A.S.; Goyal, S.B.; Raboaca, M.S.; Mihaltan, T.C.; Verma, C.; Suciu, G. Energy-Efficient Network Protocols and Resilient Data Transmission Schemes for Wireless Sensor Networks—An Experimental Survey. *Energies* **2022**, *15*, 8883. [CrossRef]
4. Kandris, D.; Nakas, C.; Vomvas, D.; Koulouras, G. Applications of Wireless Sensor Networks: An Up-to-Date Survey. *Appl. Syst. Innov.* **2020**, *3*, 14. [CrossRef]
5. Yick, J.; Mukherjee, B.; Ghosal, D. Wireless sensor network survey. *Comput. Netw.* **2008**, *12*, 2292–2330. [CrossRef]
6. Johnstone, I.; Nicholson, J.; Shehzad, B.; Slipp, J. Experiences from a wireless sensor network deployment in a petroleum environment. In Proceedings of the 2007 International Conference on Wireless Communications and Mobile Computing, Honolulu, HI, USA, 12–16 August 2007; pp. 382–387. [CrossRef]
7. Zhang, D.; Shi, P.; Wang, Q.G.; Yu, L. Analysis and synthesis of networked control systems: A survey of recent advances and challenges. *ISA Trans.* **2017**, *66*, 376–392. [CrossRef] [PubMed]
8. Kiesel, R.; Schmitt, S.; König, N.; Brochhaus, M.; Vollmer, T.; Stichling, K.; Mann, A.; Schmitt, R.H. Techno-Economic Evaluation of 5G-NSA-NPN for Networked Control Systems. *Electronics* **2022**, *11*, 1736. [CrossRef]
9. Ren, X.-X.; Yang, G.-H. Modified Kalman Filtering for Stochastic Nonlinear Systems Under Non-Gaussian-Lévy Noise and Cyber Attacks. *IEEE Trans. Syst. Man Cyb. Syst.* **2022**, *53*, 1222–1232. [CrossRef]
10. Caldieri, M.R.; Bigheti, J.A.; Godoy, E.P. Implementation and Evaluation of Wireless Networked Control Systems using Modbus. *IEEE Lat. Am. Trans.* **2017**, *2*, 206–212. [CrossRef]
11. Baillieul, J.; Antsaklis, P.J. Control and communication challenges in networked real-time systems. *Proc. IEEE* **2007**, *1*, 9–28. [CrossRef]
12. Hespanha, J.P.; Naghshtabrizi, P.; Xu, Y. A survey of recent results in networked control systems. *Proc. IEEE* **2007**, *1*, 138–162. [CrossRef]
13. da Silva, C.A.G.; Pedroso, C.M. Packet Loss Characterization Using Cross Layer Information and HMM for Wi-Fi Networks. *Sensors* **2022**, *22*, 8592. [CrossRef] [PubMed]
14. Silva, C.A.G.; Santos, E.L.; Ferrari, A.C.K.; Santos Filho, H.T. A Study of the Mesh Topology in a ZigBee Network for Home Automation Applications. *IEEE Lat. Am. Trans.* **2017**, *5*, 935–942. [CrossRef]
15. Ulusoy, A.; Gurbuz, O.; Onat, A. Wireless model-based predictive networked control system over cooperative wireless network. *IEEE Trans. Indus. Inform.* **2011**, *1*, 41–51. [CrossRef]
16. Afifi, G.; Halawa, H.H.; Daoud, R.M.; Amer, H.H. A ZigBee-based industrial WLAN. In Proceedings of the 2015 Tenth International Conference on Computer Engineering and Systems (ICCES), Cairo, Egypt, 23–24 December 2015; pp. 55–59. [CrossRef]
17. Park, P.; Ergen, S.C.; Fischione, C.; Lu, C.; Johansson, K.H. Wireless network design for control systems: A survey. *IEEE Commun. Surv. Tutor.* **2019**, *20*, 978–1013. [CrossRef]
18. Godoy, E.P.; Porto, A.J. Co-Simulation Tools for Networked Control Systems: Revision and Utilization. *J. Control Autom. Electr. Syst.* **2013**, *6*, 816–830. [CrossRef]
19. Gupta, R.A.; Chow, M.Y. Networked control system: Overview and research trends. *IEEE Trans. Ind. Electr.* **2010**, *7*, 2527–2535. [CrossRef]
20. Quang, N.V.A.; Yoo, M. Performance analysis of packet loss on wireless network control systems. In Proceedings of the 2014 International Conference on Information and Communication Technology Convergence (ICTC), Busan, Republic of Korea, 22–24 October 2014; pp. 185–186. [CrossRef]
21. Boggia, G.; Camarda, P.; Divittorio, V.; Grieco, L.A. A simulation-based performance evaluation of Wireless Networked Control Systems. In Proceedings of the IEEE Conference on Emerging Technologies and Factory Automation (ETFA), Palma de Mallorca, Spain, 22–25 September 2009; pp. 1–6. [CrossRef]
22. Zhang, X.M.; Han, Q.L.; Wang, Y.L. A brief survey of recent results on control and filtering for networked systems. In Proceedings of the 12th World Congress on Intelligent Control and Automation (WCICA), Guilin, China, 12–15 June 2016; pp. 64–69. [CrossRef]
23. Qu, F.L.; Guan, Z.H.; Li, T.; Yuan, F.S. Stabilisation of wireless networked control systems with packet loss. *IET Control Theor. Appl.* **2012**, *15*, 2362–2366. [CrossRef]
24. Iqbal, A.; Khayam, S.A. Accurate residual wireless channel simulation using a two-tier Markov model. *Simulation* **2012**, *8*, 1011–1019. [CrossRef]
25. Wu, B.; Lin, H.; Lemmon, M. Stability analysis for wireless networked control system in unslotted IEEE 802.15.4 protocol. In Proceedings of the 11th IEEE International Conference on Control and Automation (ICCA), Taichung, Taiwan, 18–20 June 2014; pp. 1084–1089. [CrossRef]
26. Linnarsson, F.; Cheng, P.; Oelmann, B. Analysis of the IEEE 802.15.4 standard for a wireless closed loop control system for heavy duty cranes. In Proceedings of the International Symposium on Industrial Embedded Systems (SIES), Costa da Caparica, Portugal, 4–6 July 2007; pp. 164–169. [CrossRef]
27. Silva, C.A.G.; Pedros, C.M. Mac-layer packet loss models for wi-fi networks: A survey. *IEEE Access* **2019**, *7*, 180512–180531. [CrossRef]
28. Abusubaih, M. Approach for discriminating losses in 802.11 wireless LANs. *IET Commun.* **2012**, *10*, 1262–1269. [CrossRef]
29. Hassan, S.M.; Ibrahim, R.; Saad, N.; Asirvadam, V.S.; Chung, T.D. Predictive PI controller for wireless control system with variable network delay and disturbance. In Proceedings of the 2nd IEEE International Symposium on Robotics and Manufacturing Automation (ROMA), Ipoh, Malaysia, 25–27 September 2016; pp. 1–6. [CrossRef]

30. Peng, C.; Song, Y.; Xie, X.P.; Zhao, M.; Fei, M.R. Event-triggered output tracking control for wireless networked control systems with communication delays and data dropouts. *IET Cont. Theor. Appl.* **2016**, *7*, 2195–2203. [CrossRef]
31. Lu, R.; Shu, J.; Bai, J.; Liu, S. H_∞ control for a class of wireless networked control systems. In Proceedings of the 2015 34th Chinese Control Conference (CCC), Hangzhou, China, 28–30 July 2015; pp. 6805–6809. [CrossRef]
32. Wang, Z.; Wang, X.; Liu, L. Stochastic optimal linear control of wireless networked control systems with delays and packet losses. *IET Control Theor. Appl.* **2016**, *7*, 742–751. [CrossRef]
33. Lin, Q.; Wu, G.; Liu, Q. EDP: A Wireless Network Control System Energy-Efficient Real-Time Task Scheduling Algorithm. In Proceedings of the 10th International Conference on Broadband and Wireless Computing, Communication and Applications (BWCCA), Krakow, Poland, 4–6 November 2015; pp. 512–517. [CrossRef]
34. Al-Dabbagh, A.W.; Chen, T. Modelling and control of wireless networked control systems: A fixed structure approach. In Proceedings of the IEEE Conference on Control Applications (CCA), Sydney, NSW, Australia, 21–23 September 2015; pp. 1051–1056. [CrossRef]
35. Wang, Q.; Zou, Y.; Niu, Y. Event-triggered model predictive control for wireless networked control systems with packet losses. In Proceedings of the IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER), Shenyang, China, 8–12 June 2015; pp. 1281–1286. [CrossRef]
36. Juárez-Lora, A.; García-Sebastián, L.M.; Ponce-Ponce, V.H.; Rubio-Espino, E.; Molina-Lozano, H.; Sossa, H. Implementation of Kalman Filtering with Spiking Neural Networks. *Sensors* **2022**, *22*, 8845. [CrossRef] [PubMed]
37. Schenato, L. Optimal estimation in networked control systems subject to random delay and packet drop. *IEEE Trans. Aut. Cont.* **2008**, *5*, 1311–1317. [CrossRef]
38. Ji, K.; Wei, D. Resilient control for wireless networked control systems. *Int. J. Control. Autom. Syst.* **2011**, *2*, 285–293. [CrossRef]
39. Kilinc, D.; Ozger, M.; Akan, O.B. On the maximum coverage area of wireless networked control systems with maximum cost-efficiency under convergence constraint. *IEEE Trans. Autom. Control* **2015**, *7*, 1910–1914. [CrossRef]
40. Foletto, T.D.C.; Moreno, U.F. On the performance of unscented Kalman filter with intermittent observations. In Proceedings of the 12th IEEE International Conference on Industrial Informatics (INDIN), Porto Alegre, Brazil, 27–30 July 2014; pp. 660–665. [CrossRef]
41. Kuzu, A.; Bogosyan, S.; Gokasan, M. Predictive input delay compensation with grey predictor for networked control system. *Int. J. Comput. Commun. Control* **2015**, *1*, 67–76. [CrossRef] [CrossRef]
42. Li, L.L.; Lemmon, M. Weakly coupled event triggered output feedback system in wireless networked control systems. *Discr. Event Dynam. Syst.* **2014**, *2*, 247–260. [CrossRef]
43. Hua, C.C.; Zheng, Y.; Guan, X.P. Modeling and control for wireless networked control system. *Int. J. Autom. Comp.* **2011**, *3*, 357–363. [CrossRef]
44. Zhang, W.; Bae, J.; Tomizuka, M. Modified preview control for a wireless tracking control system with packet loss. *IEEE/ASME Trans. Mechatr.* **2015**, *1*, 299–307. [CrossRef]
45. Li, W.; Wang, Z.; Zhou, G.; Zhu, Z. Design of fault tolerant wireless networked control systems. In Proceedings of the 2011 Chinese Control and Decision Conference (CCDC), Mianyang, China, 23–25 May 2011; pp. 65–68. [CrossRef]
46. Yi, H.C.; An, C.J.; Choi, J.Y. Compensation of Time-Varying Delay in Networked Control System over Wi-Fi Network. *Int. J. Comput. Commun. Control* **2017**, *3*, 415–428. [CrossRef] [CrossRef]
47. Tiberi, U.; Fischione, C.; Johansson, K.H.; Di Benedetto, M.D. Energy-efficient sampling of networked control systems over IEEE 802.15.4 wireless networks. *Automatica* **2013**, *3*, 712–724. [CrossRef]
48. Zhang, W.; Tomizuka, M.; Wei, Y.H.; Leng, Q.; Han, S.; Mok, A.K. Robust time delay compensation in a wireless motion control system with double disturbance observers. In Proceedings of the American Control Conference (ACC), Chicago, IL, USA, 1–3 July 2015; pp. 5294–5299. [CrossRef]
49. Sun, Y.-C.; Yang, G.-H. Event-triggered state estimation for networked control systems with lossy network communication. *Inform. Sci.* **2019**, *492*, 1–12. [CrossRef]
50. Ren, X.-X.; Yang, G.-H. Multi-sensor Kalman filtering over packet-dropping networks subject to round-robin protocol scheduling. *J. Frankl. Inst.* **2021**, *358*, 7938–7954. [CrossRef]
51. Ling, Q.; Lemmon, M.D. Optimal dropout compensation in networked control systems. In Proceedings of the 42nd IEEE Conference on Decision and Control, Maui, HI, USA, 9–12 December 2003; pp. 670–675. [CrossRef]
52. Texas Instruments. CC2531 USB Evaluation Module Kit. Available online: https://www.ti.com/tool/CC2531EMK (accessed on 5 January 2023). [CrossRef]
53. Jwo, D.-J.; Biswal, A. Implementation and Performance Analysis of Kalman Filters with Consistency Validation. *Mathematics* **2023**, *11*, 521. [CrossRef]