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Optimum Compensation of Packet-Loss over IEEE 802 Standard-Based Blackhole for DC Motor Speed Control

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ABSTRACT

DC motors are utilized throughout multiple industries due to their superior performance, characterized by high torque and compact size. A PID controller and compensator are suggested to manage and mitigate packet loss in WNCS. The literature review indicates that many researchers utilize wire systems, and some use a WNCS like IEEE802.15.4 and a PID controller with different methods to tune the PID. This paper presents an overview of the functioning of a wireless communication network, focusing specifically on the effect of packet loss on the speed of the DC motor. Packet losses and time delays encountered during data transmission and reception in the wireless network pose significant challenges. Packet loss issues can compromise the WNCS accuracy and potentially impact the entire system's stability. This research proposes the transfer of the control signal generated using the PID controller. The PID was tunned by using the Black Hole optimization technique and transmitted wirelessly using IEEE 802.15.4 and IEEE 802.11b and a compensator at the plant side to mitigate the anticipated packet loss effects. Our system is designed to withstand data loss of up to when using a 60%compensator. Our solution employs real-time implementation alongside MATLAB and a truetime emulator to model wireless network control systems (WNCS).

1. INTRODUCTION

Traditionally, networked control systems rely on wired communication networks for information transfer within the closed-loop control system. However, this approach has limitations, particularly in system distribution and scalability of applications. Therefore, wireless communication networks emerge as viable alternatives to their wired equivalents [1, 2]. Advancements in sensor technology have expanded the scope of wireless communication technologies beyond just office and home use to industrial applications, including manufacturing, industrial monitoring, and control networks. There are many advantages to using NCS systems, including lower cost, more straightforward installation, and greater adaptability to harsh environments [3]. Consequently, the WNCS has attained global attention [4, 5]. In WSNs, Sensor nodes gather information from the physical process and wirelessly transfer it to the controller, which processes it, computes, regulates commands, and transmits it to the actuators within the system [1, 6]. Still, the limitation and the issue we face in using WNCS is packet loss. When the packet loss rises, The WNCS could become unreliable due to a decline in system stability [7]. So, with good wireless technology, a robust control system, and a strong compensator (PID) to attain reliable and real-time performance it is essential to develop and implement a robust communication and control system [8, 9]. The optimal functioning of Industrial Wireless Sensor Networks (IWSNs) hinges on the creation of a method capable of effectively managing packet loss [10].

The functioning of Wireless Networked Control Systems (WNCS) has been examined [11, 12]. Millan et al. [11] provided a brief analysis of the fundamental characteristics of WNCS, including techniques and protocols for addressing network-induced delays. Meanwhile, this study proposes wireless control methods for an inverted pendulum based on key concepts introduced in the study [12]. PID and LQR algorithms were implemented to control systems that operate over unreliable wireless network links [13-17]. The study [13] contrasts PID and Neural Networks for regulating a wired DC motor system. The result appears that the Neural Network is better than PID for an extended period. Hasan et al. [14] used a PID and FOPID to control a wired inverted pendulum system and used a grey wolf to tune the FOPI-FOPD. When comparing PID and fuzzy PID, the result showed that fuzzy PID performed better than PID controllers in wired control systems [15]. Prasad et al. [16] used a PID and LQR controller to control a nonlinear inverted pendulum for the wired control system, and Hasan et al. [17] used WNCS to control an inverted pendulum by using a PID and FOPID. The study [18] used a predictive compensator to reduce forward channel packet loss, demonstrating its effectiveness in improving control system performance. The PID controller was created for wired network control systems without considering packet loss and using different tuning techniques, PID tuner app, modified Ziegler-Nichols method, and genetic algorithm (GA) [19]. However, in our research, none of the previous researchers used PID in WNCS or tried to compensate for the packet loss during transmission, so we modified the PID to compensate for packet losses on the reverse channel. This enhanced PID determines the best control value by estimating the optimal value and considering the plant's state. Rojas et al. [20] employed to compensate for packet losses in the forward, backward, and both channels through the utilization of a Predictive Compensator in a Forward Loop, Modified LQR in a Backward Loop, and a Combination of Predictive and Modified LQR Compensators on Both Sides. The control system's performance [21] was improved by combining Predictive and Modified LQR Compensators on Both Sides to compensate for the packet loss in both channels. The study [3] used IEEE 802.15.4 for packet transmission for a control signal produced by the PID controller to the DC Motor plant. The researcher used a Kalman Filter and Gilbert-Elliot as a compensator to reduce the packet loss impact on the system stability in the research not appear the effect with high packet lose out use another wireless technology like IEEE 802.11. The literature mainly focuses on wired network controls, with some studies addressing packet loss in Wireless Networked Control Systems (WNCS) using IEEE 802.15.4 protocol, which is not ideal for long-distance communication and interference resistance compared to the IEEE 802.11/b standard. This study employs a PID as a compensator method to analyze the process's behavior when packet loss occurs in a control system's (forward and feedback) channels. The result was calculated from closed-loop control over an 802.11/b WNCS. This study includes two major contributions: first, an analysis of the performance of IEEE 802.11 Wi-Fi in modeling packet loss; second, the application of a PID controller as a compensatory mechanism to mitigate the impacts of packet loss and time delay. The evaluation of non-compensator versus compensated behavior was conducted utilizing metrics: Root Mean Square Error (RMSE) In this study, we employ a Black Hole optimization technique to tune the PID controller, which leads to an effect on system stability [22].

To evaluate the proposed compensator, it was tested using an unstable system and DC motor speed control in simulations using MATLAB Simulink and truetime under varying packet loss rate conditions, demonstrating its effectiveness in withstanding high rates.

2. WIRELESS NETWORK CONTROLLED SYSTEM

The overall architecture of Wireless Networked Control Systems (WNCS) is depicted in Figure 1 [23]. Within the Wireless Sensor Network (WSN), the primary function of the sensor node is to observe and track the various parameters of the plant. The data is transmitted via wireless means to the reference node, which is analyzed as outlined in the study [24]. An actuator is controlled by a signal sent based on the received feedback signal. This signal is essential for maintaining the system's stability and preemptively averting potential failures.

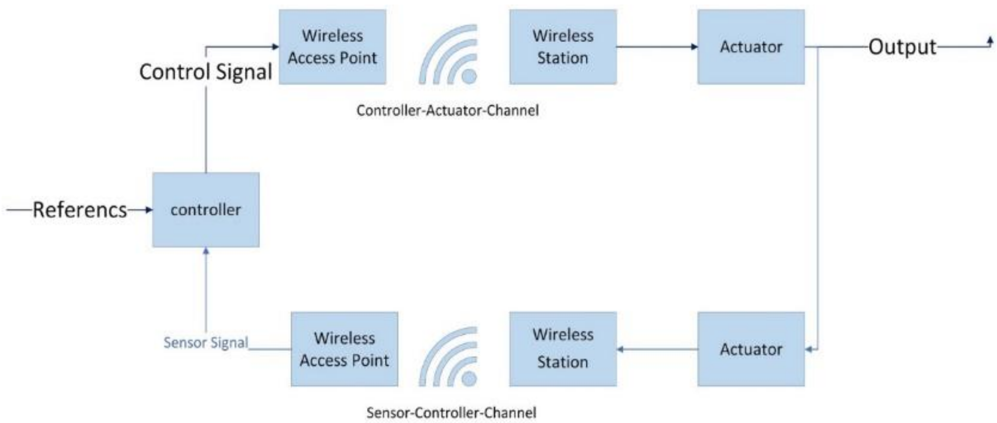

Figure 1. The general structure of WNCS

2.1 Packet loss in wireless network

Packet loss is a critical factor that must be managed to attain the desired performance of wireless networks [25]. Packet loss poses a considerable challenge for wireless networks and profoundly affects the perceived quality of numerous services. Various factors, such as interferences, coexistence, fading, collisions, buffer size, and so on, can cause packet losses [26].

2.2 DC motor background

The motor comprises two primary parts: an electrical part and a mechanical part [27, 28]. A DC motor is an actuator that converts electrical energy into mechanical energy and is commonly utilized in industrial applications. The critical advantage of DC motors lies in their capacity for speed control. The proportional-integral-derivative (PID) controller has been widely used as a staple in industrial process control for decades [29]. PID controllers remain predominant in industrial settings, accounting for about 95% of all controllers due to their simplicity, effectiveness, and ease of use [30, 31]. DC motor speed control is deliberately altering the driving speed to a value necessary for completing the specified task. The mathematical model for a controlled DC motor is provided by the following transfer function [3].

$$G(S) = \frac{3.779s + 2.554}{s^2 - 0.3654s + 0.3286} \tag{1}$$

2.3 Controller system design

Controller system plays a critical role in modern technology and automation, enabling precise control and optimization of various processes and systems. The PID control systems widely use feedback control mechanisms employed in various systems and we will use them in our system as a compensator.

A PID compensator is employed in control systems and comprises three separate gains: proportional, integral, and derivative. These are the instantaneous actual value given by the proportional term, the accumulated past values given by the integral term, and the predicted future values provided by the derivative term. This mechanism maintains the output, such as a setpoint, at a specific, predetermined level. PID controllers are utilized in analog and digital formats, finding applications in various fields such as temperature regulation and engine rotational speed control [20, 32]. The PID compensator functionality is characterized by a specific relationship between the target input e(t), and its output, u(t), which is then applied to the motor. This relationship is defined by the controller's Eq. (2) [33].

$$u(t) = K_p e(t) + k_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{2}$$

2.4 Black whole optimization technique

The Black-Hole Optimizer (BHO) is a nature-inspired optimization algorithm that uses metaheuristic approaches to address engineering optimization challenges [34]. This technique applies physical behaviors derived from natural evolutionary principles to tackle diverse engineering optimization difficulties [35, 36]. The BHO algorithm mimics the interactions between stars and black holes at the center of galaxies, employing straightforward mathematical rules. This approach facilitates exploring and exploiting the solution space in engineering problems. In general, this technique enables solving large-scale nonlinear optimization problems through heuristic exploration of the solution spaces [35]. BHO is a population-based optimization algorithm, with stars representing individuals and black holes representing the best current solution. The operation flow chart of the algorithm is shown in Figure 2 [37].

$$\begin{gathered} x_i(t+1)x_{i(t)} + rand * (G_{best} - x_i(t)) \\ G_{best} \neq x_i(t), i = 1, 2, \ldots, n \end{gathered} \tag{3}$$

2.5 Proposed model

The speed control system has been designed as shown in Figure 3, and is simulated using MATLAB and a true-time simulator. The speed of the DC motor was regulated using PID controllers, with the control and feedback signals transmitted via a wireless network. The loss of data packets transmitted between the actuator, controller, and sensor can lead to the failure of the control system. This requires the development of a control system that can effectively manage packet losses and minimize their consequences.

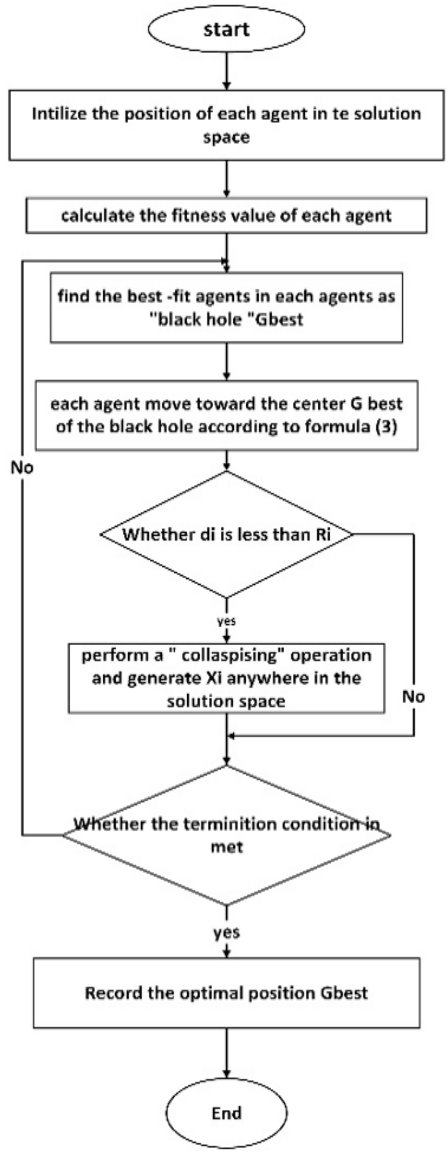

Figure 2. Flowchart of blackhole optimization

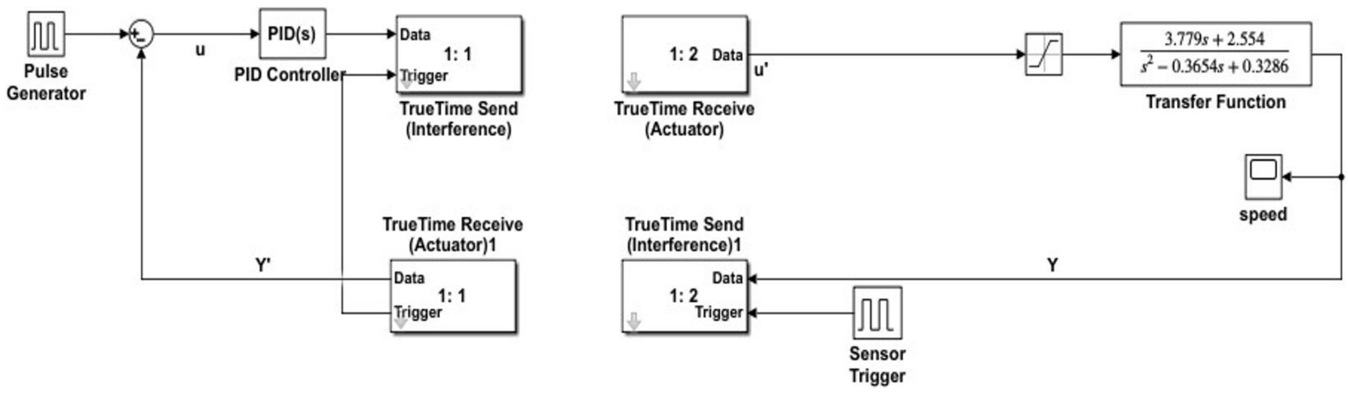

Figure 3. The design of WNCS

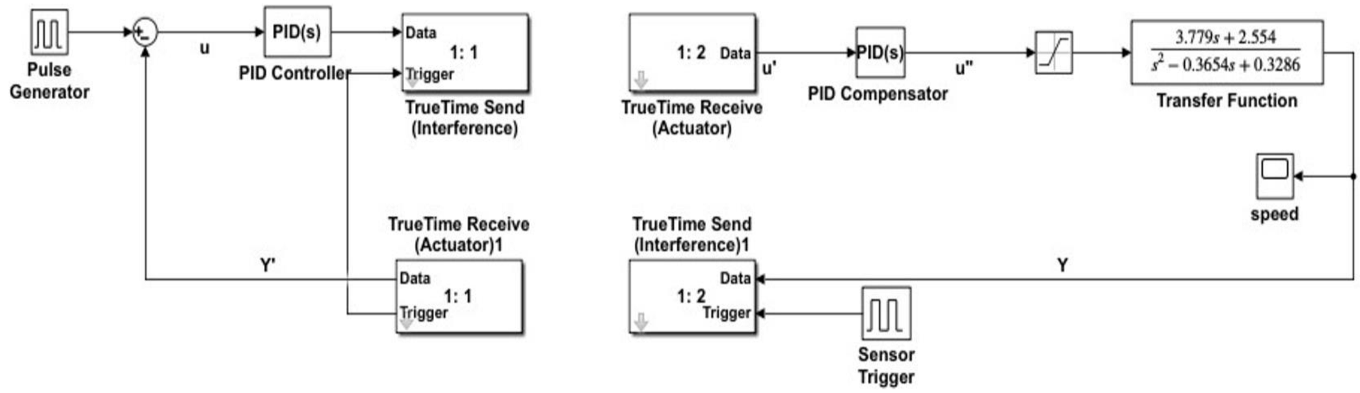

Figure 4. The design of WNCS with compensator

Figure 3 illustrates the function of two control signals within the system: u refers to the control signal at the controller side, while u' refers to the control signal at the plant side, which may experience packet loss during transmission. The expression of can be formulated as follows [6]:

$$u' = u(1 - \delta_u) \tag{4}$$

Let δ_u represent the rate at which packets are lost in the feed-forward loop. The range of values for δ_u is from 0 to 1. Y represents the system's output signal at the plant, while Y' represents the system's output signal at the controller. The signal at the controller may be impacted by packet loss in the feedback loop during transmission. The equation for Y' can be defined as follow [6]:

$$\acute{y} = y(1 - \delta_y) \tag{5}$$

where, δ_y represents the rate at which packets are lost in the feedback. The range of δ_y is from 0 to 1. The suggested compensator can maintain system stability within a packet loss range of 0% to 60%. In order to address the situation where the packet loss rate exceeds 60%, the PID controller on the plant side has been utilized as a form of compensation. Figure 4 depicts the system block diagram, which includes a compensator.

3. RESULT AND DISCUSSION

The simulation the DC Motor process and analyze the reliability of the data packets that are sent and received between nodes in the network by using IEEE 802.15.4 and IEEE 802.11b, the control parameters were parameterized using Simulink with PID controller. The WNCS is shown in Figure 4. PID Gain parameters to control the speed of DC Motor calculated by using Black Hole Optimization. The metric that was employed to evaluate the system performance was the Root Mean Square Error (RMSE) This is computed using Eq. (6) [3]:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - ri)^2} \tag{6}$$

where, N=Number of Simple, y_i=observed values, ri=modeled values.

Two scenarios were used to present the results. In the first scenario, the data is transmitted via 802.15.4. In the second scenario, the data is transmitted via IEEE 802.11b.

3.1 First scenario with IEEE 802.15.4

The results of the WNCS analysis using IEEE 802.15.4 with a sensor trigger for wireless nodes showed a period value of 0.009 (sec) and an amplitude of 5. The RMSE evolution for WNCS without a compensator ranged between 0.0003263 and 0.0003624, as depicted in Figure 5. The RMSE for WNCS with a compensator varied between 0.0002405 and 0.0002951, as shown in Figure 6, confirming the compensator's efficiency and improvement.

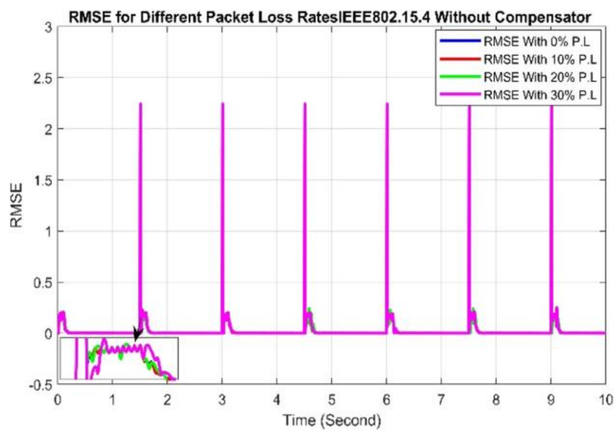

Figure 5. RMSE value without compensator

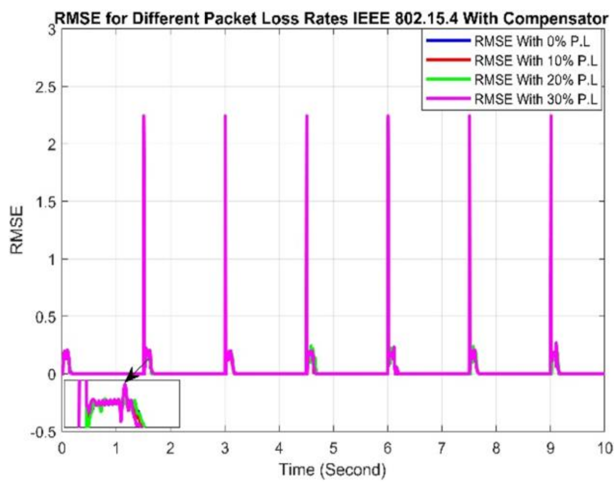

Figure 6. RMSE value with compensator

Figure 7 illustrates the system response under packet loss without a compensator, while Figure 8 demonstrates the enhancement in system behavior when using the compensator.

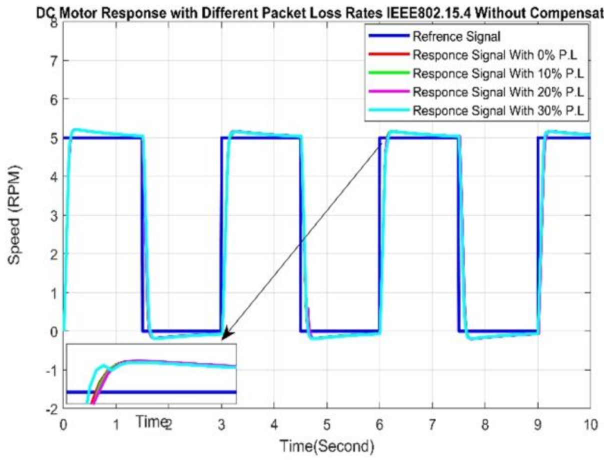

Figure 7. System response with packet loss without a compensator

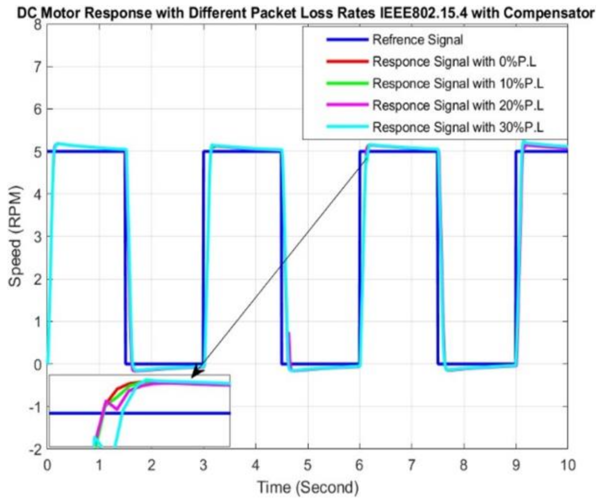

Figure 8. System response with packet loss with a compensator

3.2 Second scenario with IEEE 802.11b (Wi-Fi)

The result of the WNCS with Wi-Fi analysis results with a sensor trigger period value of 0.001 and amplitude of 5.

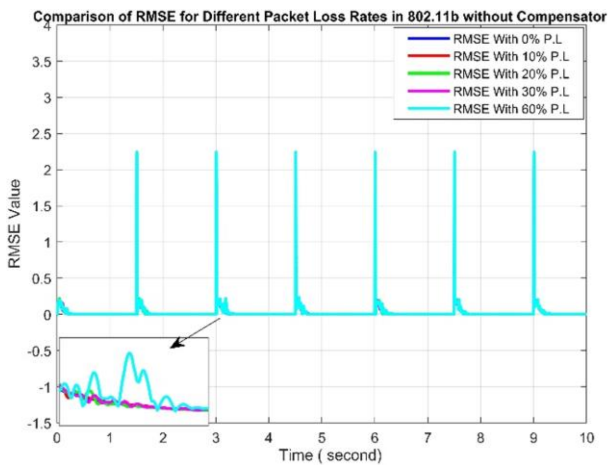

Figure 9. RMSE value without compensator

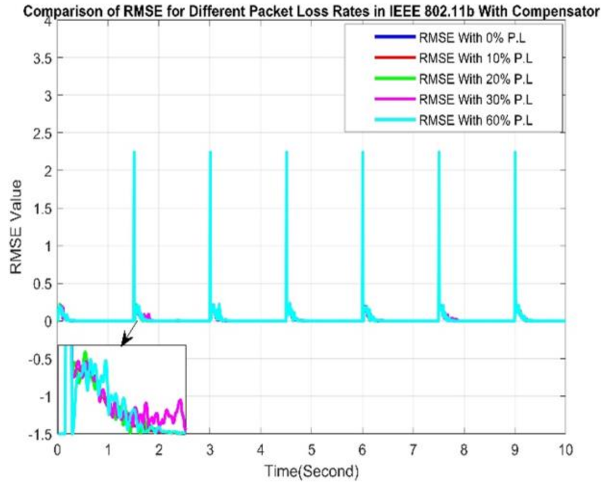

Figure 10. RMSE value with compensator

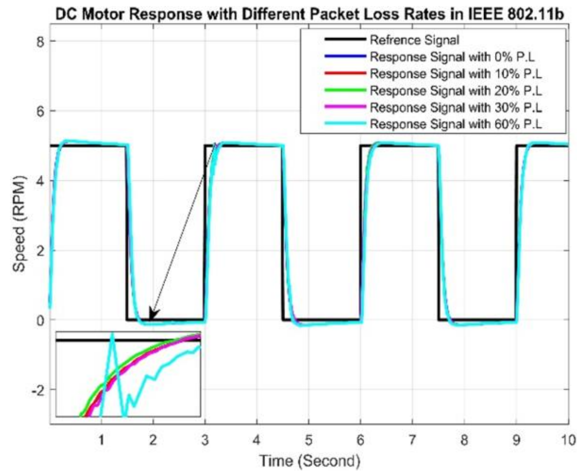

Figure 11. System response of packet loss without a compensator

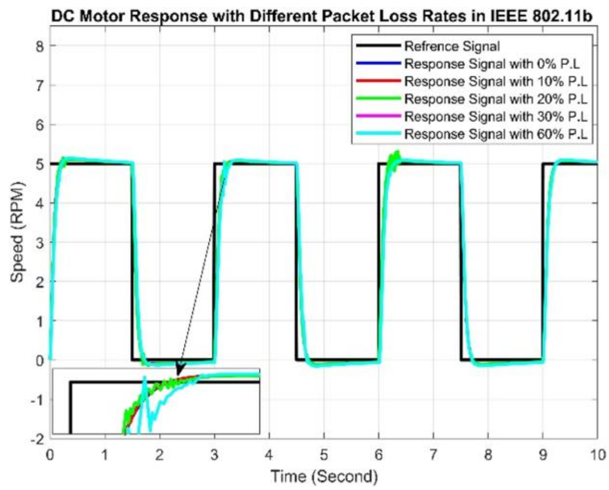

Figure 12. System response of packet loss with a compensator

The RMSE evolution for WNCS without compensator between (0.0002232 and 0.0002881) as shown in Figure 9 and the RMSE for WNCS with compensator between (0.0001804 and 0.0002152) as shown in Figure 10 that confirmed the improvement and the efficiency of the compensator. Figure 11 illustrates the system response with packet loss without a compensator, while Figure 12 demonstrates the improvement in system behavior with the compensator.

3.3 Real time implementation of WNCS using Wi-Fi

The real-time closed-loop wireless control systems using IEEE 802.11 Wi-Fi still lack implementation and realization.

Figure 13. Real time implemention

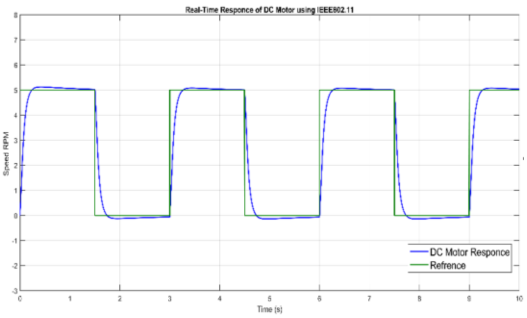

Figure 14. System response of DC motor with real-time implementation

Therefore, the system will be implemented in real-time design by presenting in laptop computers, one as a sender (controller) and another one as a receiver (plant), as shown in Figure 13. And the control signal will be sent between the control side and plant side through the IEEE 802.11 Wi-Fi constructed by a Wireless Network Interface Card (WNIC) that is embedded in the laptop. Figure 14 shows the response of the DC motor by using IEEE802.11.

4. COMPRESSION RESULT

In this section we will present the work compression for real time implementation with simulation in IEEE802.11 and for Zigbee with related work and as below.

4.1 Compression real-time implementation with simulation-time

From the previous result of real-time implementation and simulation-time the result show in Table 1. the performance of real-time is closed to the simulation result.

4.2 Compression with a published related work

The study [3] used a Kalman filter with a PID controller that was tuned by the root locus method to control a DC motor panel and control signal transmission via IEEE 802.15.4. When we compare the PID controller that was tuned via BHO and used a PID as a compensator, it is better than the Kalman filter as shown in Table 2.

Table 1. Compression real-time implementation with simulation-time

Method	Rise Time (s)	Settling Time (s)	Overshoot	RMSE
Simulation (IEEE802.11)	0.102	0.2	0.07	0.0002232
Real-time implementation (IEEE802.11)	0.13	0.25	0.102	0.0003423

Table 2. Comparison results with related work in IEEE 802.15.4

Error Types	0% P.L.	10% P.L.	20% P.L.	30% P.L.
RMSE without PID compensator	0.0003263	0.0003624	0.0003391	0.0003469
RMSE with PID compensator	0.0002405	0.0002752	0.0002508	0.0002951
RMSE with Kalman [3]	0.9942	1.0167	0.9915	1.1024

5. CONCLUSION

This research addresses a critical challenge in Wireless Networked Control Systems (WNCS): the impact of packet loss on the stability and performance of DC motor speed control. By integrating IEEE 802.15.4 and IEEE 802.11b wireless communication standards and employing a PID controller with a compensator, the study demonstrates a novel approach to mitigate packet loss effects. The PID parameters are optimally tuned using the Black Hole Optimization (BHO) algorithm, enhancing the controller's robustness under high packet loss conditions.

Simulations and real-time implantation conducted in MATLAB/Simulink and True-time Simulator validate the system's effectiveness, showing the compensator's capability to sustain system stability even with packet loss rates as high as 60% according the Figure 12. Furthermore, the evaluation using Root Mean Square Error (RMSE) confirms the reliability of the proposed compensation strategy.

This study's contributions lie in the dual focus on analyzing the performance of wireless technologies for packet loss modeling and demonstrating the efficacy of a PID compensator in a WNCS environment.

These insights provide a robust foundation for further research and practical applications in industrial automation, particularly in systems requiring real-time performance over wireless networks. Future work could explore adaptive compensation techniques and alternative optimization methods further to enhance system performance under extreme packet loss conditions.

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