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MPC Based Power Allocation for Reliable Wireless Networked Control Systems

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ABSTRACT This paper considers a wireless networked control system (WNCS) where the controller and controlled object (plant) are connected via an unreliable wireless network. The control system should be designed considering the reliability of the given network while its network reliability is controllable by changing transmission power. Thus, this paper provides a joint optimization of transmission power and control-input for the focused WNCS, which is a kind of cross-layer design of communication and control layers. This work assumes that the total transmission power for the feedforward (from the controller to plant) and feedback (from the plant to controller) channels is limited and can be adaptively allocated to each wireless channel. If more transmission power is allocated to the feedforward channel, the control-input can be more reliably transmitted, while the control-state is less reliably transmitted over the feedback channel. Furthermore, the appropriate power allocation depends on the control-state and the previous communication results. Considering the above facts, this paper proposes a model-predictive control (MPC) based joint optimization and shows that the proposed system can provide appropriate power allocation and control-input and thus can enhance the quality of control.

INDEX TERMS Wireless networked control system, power allocation, model predictive control, UDP.

I. INTRODUCTION

In the last few decades, the rapid development of control, computer, sensor, and communication technologies has changed the structure of control systems to networked control systems (NCSs). This paper focuses on a *wireless* networked control system (WNCS) where the plant to be controlled and the controller are separately located and are connected via wireless links. Recently, WNCSs have gained significant popularity in the research field of factory(industrial) automation, smart grid and so on, due to many benefits such as system mobility, reconfigurability, and reasonable installation cost. For more on the general topic of NCS, see, e.g., [1], [2] and the references therein. To realize a reliable WNCS, we have to consider the features of wireless communication such as data rate limitation, transmission delay, and communication errors. However, most of the studies in WNCS are tackled by researchers of control theory. For example, in order to suppress the impact of communication error, Kalman filter-based observer and linear quadratic optimal controller have been studied in [3], [4]. The impacts of quantization error and packet loss on the NCS has been investigated in [5], [6]. The robust stability condition for the NCS with finite data rates and packed losses has been provided in [7], [8].

More recently, a new approach of cross layer design between communication and control theories has been studied because a joint consideration from both control and communication approaches can achieve further improvement of the control performance and more efficient communication cost [9]–[14]. In [10], [11], the joint optimization for the control-input and the transmission power in feedback channel has been provided in order to achieve efficient transmission power cost. The literature [12] considers a joint optimization of the transmission power and control-input for the scenario where multiple pairs of NCS share their wireless communication resources. The literature [13] has provided the joint optimization of control-input and scheduling algorithm for IEEE 802.15.4 based WNCS. In [14], the maximum-likelihood (ML) decoder exploits the estimation results calculated by the observer for the estimation of the signal received from the sensor as a-priori information and then can enhance the

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decoding (communication) performance. However, most of the works based on a cross-layer design have assumed that the feedforward channel can be ideally communicated or the controller side can ideally know the received result at the plant.

The communication protocol can be roughly categorized into transmission control protocol (TCP) and user datagram protocol (UDP) [15]. In the TCP-based communication, the transmitter can know the communication result by receiving acknowledgement (ACK) or negative-acknowledgement (NACK) signal from the receiver. In a general wireless data communication, if the failure of transmission is detected, the transmitter tries to re-transmit the signal for realizing reliable communication, which is referred to as automatic repeat request (ARQ). However, ARQ is not suitable for the control system, because the re-transmitted data is not optimal control-input or accurate control-state due to the time-delay caused by the re-transmission. In the UDP-based communication, the transmitter can be implemented more simply than the one with TCP, but the transmitter cannot detect the communication result. Thus, in the UDP-based WNCS, if the communication error at the feedback channel occurs, the estimation result calculated by the observer has the uncertainty of whether the control-input has been successfully transmitted (input) to the plant or not. The literature [4] has provided the calculation of the control-input and estimation method depending on the applied communication protocol (i.e., TCP or UDP), but it has not considered the design of the communication systems. The communication reliability at the feedforward and feedback channels can be controlled by changing transmission power.

This work assumes that the total transmission power is limited, and considers how to allocate the transmission power into feedforward and feedback channels. For instance, when more transmission power is allocated into the communication of the feedforward channel, the control-input can be more reliably received at the plant, but the feedback information (control-state) is less reliably received at the controller. Furthermore, when the communication at the feedback channel fails, the controller needs to estimate the control-state from the previous estimated results and the previous control-input while considering the communication reliability at the feedforward channel. As a result, the communication reliability at the feedforward and feedback channels affects the optimal control-input, while the accuracy of the estimated control-state affects the optimal power allocation. Therefore, this work tries to optimize both power allocation and calculation of control-input based on a model predictive control (MPC). The power allocation is a common problem in wireless communications systems. There are many sophisticated power allocation methods, e.g., [16], [17]. The study approach of [17] is similar to this work in terms of cross-layer optimization. Reference [17] has provided an optimum power allocation method considering the quality of application-layer for video communication systems. This work also provides a power allocation method considering the quality of control system. However, it is worth noting that our approach tries to optimize not only power allocation, but also the corresponding control-input by using MPC-based optimization.

MPC is a control method where the control-input is given by solving the finite-time optimal control problem at each control-interval, which can easily solve the optimization problem, satisfying the constraints of state and/or control-input. Recently, several MPC schemes considering the probabilistic model (event) have been proposed, which are referred to as stochastic MPC (SMPC) [18]–[26]. Most of the works on SMPC focus on the control law and/or optimization method considering the focused uncertainty such as a disturbance in control plant, control-model mismatch, and so on. The works [25], [26] have tackled the uncertainty which depends on both the control-state and control-input similar to the problem focused in this work. However, it does not consider the design of communication which affects the uncertainty. Therefore, in order to make a reliable WNCS, it is necessary to optimize a communication-system as well as a control-system. This work first makes the model of the WNCS correspond to the probabilities of the communication error at the feedforward and/or feedback channels and provides the cost function considering the quality of control at the plant and the accuracy of estimation at the controller. Then, to minimise the defined cost function, the joint optimization of power allocation and control-input is realized based on (S)MPC optimization.

The main contributions of this work are summarized as follows:

- The cost function based on the quality of control and the accuracy of estimation depending on the probabilities of communication error at the feedforward and feedback channels are provided.
- This work provides a joint-optimization of the control-input and the transmission power at the feedforward and feedback channels.
- The proposed optimization is designed corresponding to the applied communication protocol.
- Computer simulations show that the proposed optimization can adaptively change the transmission power and give the optimal control-input depending on the quality of control and the accuracy of the estimation result, which can enhance the robustness and reliability of the WNCS over fading channel.

The rest of this paper is organized as follows: In Sec.II, the focused WNCS is presented where the controller and plant are connected via un-reliable wireless links. In Sec.III, the impacts of the communication errors at the feedforward and feedback channel depending on the communication protocol are formulated. In Sec.IV, the joint optimization methods corresponding to the communication protocol are proposed. In Sec.V, some numerical evaluations are presented to validate the efficiency of the proposed optimization. Lastly, the conclusions are drawn in Sec.VI.

Notation: Let $\mathbb{R}$ denote the set of real numbers. For the vector v, let v^T denote the transpose of v. For brevity, we sometimes use the symbol "0" instead of zero matrix with appropriate dimensions and omit the index of vector. Let $\Pr(x)$ and $\mathbb{E}[X]$ be the probability of the event x and the expected value of a random variable X, respectively.

II. SYSTEM MODEL

The WNCS focused in this work is composed of four parts; observer, controller, controlled object (plant), and sensor, as depicted in Fig.1. The observer and controller are embedded in the controller side, while the controlled object and sensor are in plant side. The controller and plant are connected through wireless networks. The channels from controller to controlled object and from sensor to observer are referred to as feedforward and feedback channels, respectively. This work focuses on a discrete-time control since we consider a digital wireless communication. The communication network and control system can be modeled as follows.

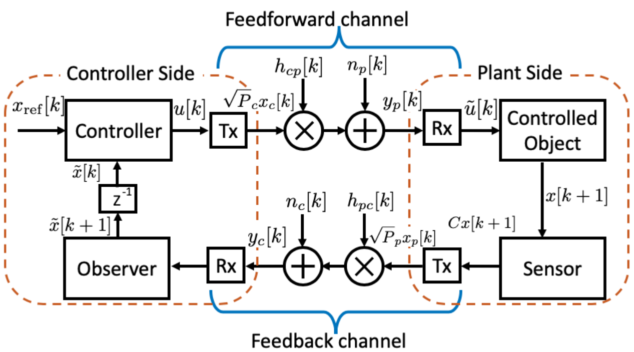

FIGURE 1. Wireless Networked Control System.

A. WIRELESS COMMUNICATION CHANNELS

The controller at the controller side wants to transmit the control-input $u[k]$ to the controlled object at the plant side through the feedforward wireless channel, while the sensor at the plant side wants to transmit the measured control-state $Cx[k]$ to the observer at the controller side through the feedback wireless channel. The details of control-input and measured control-state will be described in the next subsection. Assuming that $x_c[k]$ and $x_p[k]$ are the transmitting signals from the controller and sensor at the kth time slot and with average power of 1 ($\mathbb{E}[|x_c[k]|^2] = \mathbb{E}[|x_p[k]|^2] = 1$). They are composed of the control-input $u[k]$ and measured control-state $Cx[k]$. The received signals at the controlled object (plant) and observer are respectively given by

$$y_p[k] = h_{cp}[k]\sqrt{P_c[k]}x_c[k] + n_p[k] \tag{1}$$

$$y_c[k] = h_{pc}[k]\sqrt{P_p[k]}x_p[k] + n_c[k], \tag{2}$$

where $h_{cp}[k]$ and $h_{pc}[k]$ are the Rayleigh-fading coefficients in the feedforward and feedback channels and independently drawn from the complex Gaussian distribution $\mathcal{CN}(0, 1)$. $P_c[k]$ and $P_p[k]$ are the transmitting power at the controller and plant. $n_p[k]$ and $n_c[k]$ are the noise factors which follow Gaussian distributed random variables with mean zero and variances N_p and N_c ($n_p \sim \mathcal{CN}(0, N_p)$, $n_c \sim \mathcal{CN}(0, N_c)$). This work assumes that channel estimation and time-frequency synchronization at the receiver side are perfect. Let R_c and R_p be the transmission rates from controller to plant (for the information of control-input) and from plant to controller (for the information of plant-state). In this case, the outage probabilities of the feedforward and feedback channels are given by

$$p_{cp}[k] = \Pr\left(\log_2\left(1 + \frac{|h_{cp}|^2 P_c[k]}{N_p}\right) < R_c\right) = 1 - \exp\left(-\frac{N_p\left(2^{R_c} - 1\right)}{P_c[k]}\right), \tag{3}$$

$$p_{pc}[k] = \Pr\left(\log_2\left(1 + \frac{|h_{pc}|^2 P_p[k]}{N_c}\right) < R_p\right) = 1 - \exp\left(-\frac{N_c\left(2^{R_p} - 1\right)}{P_p[k]}\right). \tag{4}$$

Two types of transmission protocols, that is, transmission control protocol (TCP) and user datagram protocol (UDP), are typically used in wireless communication systems. In a TCP-based transmission, the transmitter side can detect whether the transmitted signal could be successfully received or not by using ACK/NACK signals. We further assume that the receiver can ideally detect the communication error. Although an automatic repeat request (ARQ) is generally used in a TCP transmission for realizing a reliable communication, this work does not consider it because ARQ causes a communication delay and its delay has a deep impact on the control systems. In a UDP-based transmission, the transmitter side cannot know the communication results but the communication systems at both transmitter and receiver sides can be more simply implemented. This work applies either TCP or UDP to the focused WNCS.

B. CONTROL SYSTEM

Consider a linear time-invariant system of the discrete-time form

$$x[k+1] = Ax[k] + Bu[k] \tag{5}$$

$$y[k] = Cx[k], \tag{6}$$

where $x[k] \in \mathbb{R}^{n_x}$, $u[k] \in \mathbb{R}^{n_u}$, and $y[k] \in \mathbb{R}^{n_y}$ denote the state of the controlled object (control-state), control-input, and measured output at sampling instant k, respectively. $A \in \mathbb{R}^{n_x \times n_x}$, $B \in \mathbb{R}^{n_x \times n_u}$, and $C \in \mathbb{R}^{n_y \times n_x}$ are the coefficient matrices of the control system. This work does not consider the disturbance at the controlled object and the sensing error at the sensor because we would like to focus only on the impacts of communication quality on the control system. In order to get the optimal control-input, we utilize a MPC based optimization [18]–[26]. Assuming that an error-free communication at both feedforward and feedback channels can be realized, the perfect knowledge of the control-state $x[k]$ and control-input $u[k]$ are available at both sides. The optimal control-input at the kth time-slot can be calculated as

$$u^{\text{opt}}[k] = \left(\mathbf{U}^{\text{opt}}[k]\right)_1, \tag{7}$$

$$\mathbf{U}^{\text{opt}}[k] = \arg\min J_k(\mathbf{U}), \tag{8}$$

$$J_k(\mathbf{U}) = \sum_{n=0}^{N-1} \Big(x[k+n]^T Q x[k+n] + u[k+n]^T R u[k+n]\Big) + x[k+N]^T P x[k+N], \tag{9}$$

where $\left(\mathbf{U}^{\text{opt}}[k]\right)_1$ is the first n_u elements of $\mathbf{U}^{\text{opt}}[k] (\in \mathbb{R}^{Nn_u})$ which corresponds to the control-input at the kth time-slot, $P \geq 0$, $Q \geq 0$, and $R > 0$ are weight matrices and N is the receding horizon (prediction period). Applying the matrix form defined as

$$\underbrace{\begin{bmatrix} x[k+1] \\ x[k+2] \\ \vdots \\ x[k+N] \end{bmatrix}}_{\triangleq \mathbf{X} \in \mathbb{R}^{Nn_x}} = \underbrace{\begin{bmatrix} A \\ A^2 \\ \vdots \\ A^N \end{bmatrix}}_{\triangleq \mathbf{A} \in \mathbb{R}^{Nn_x \times n_x}} x[k] + \underbrace{\begin{bmatrix} B & 0 & \cdots & 0 \\ AB & B & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A^{N-1}B & A^{N-2}B & \cdots & B \end{bmatrix}}_{\triangleq \mathbf{B} \in \mathbb{R}^{Nn_x \times Nn_u}} \underbrace{\begin{bmatrix} u[k] \\ u[k+1] \\ \vdots \\ u[k+N-1] \end{bmatrix}}_{\triangleq \mathbf{U} \in \mathbb{R}^{Nn_u}}, \tag{10}$$

$$\mathbf{X} = \mathbf{A}x[k] + \mathbf{B}\mathbf{U}, \tag{11}$$

Equation (9) can be rewritten as

$$\begin{aligned} J_k(\mathbf{U}) &= \mathbf{X}^T \bar{Q} \mathbf{X} + \mathbf{U}^T \bar{R} \mathbf{U} \\ &= (\mathbf{A}x[k] + \mathbf{B}\mathbf{U})^T \bar{Q} (\mathbf{A}x[k] + \mathbf{B}\mathbf{U}) + \mathbf{U}^T \bar{R} \mathbf{U} \\ &= \mathbf{U}^T \left(\bar{R} + \mathbf{B}^T \bar{Q} \mathbf{B}\right) \mathbf{U} + 2\, x[k]^T \mathbf{A}^T \bar{Q} \mathbf{B} \mathbf{U} \\ &\quad + x[k]^T \mathbf{A}^T \bar{Q} \mathbf{A} x[k], \end{aligned} \tag{12}$$

where

$$\bar{Q} = \begin{bmatrix} Q & 0 & \cdots & 0 & 0 \\ 0 & Q & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & Q & 0 \\ 0 & 0 & \cdots & 0 & P \end{bmatrix} \in \mathbb{R}^{Nn_x},$$

$$\bar{R} = \begin{bmatrix} R & 0 & \cdots & 0 \\ 0 & R & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & R \end{bmatrix} \in \mathbb{R}^{Nn_u}. \tag{13}$$

Since the cost function $J_k(\mathbf{U})$ is quadratic and the weight matrices are positive (semi)definite, the optimization problem given by (8) can be solved as a convex quadratic programming (QP) problem. It is well-known that this optimization problem has a unique minimum and can be efficiently solved by using standard techniques [27], [28]. Since the optimization problem given by (8) is solved in a receding-horizon manner, only the first element of the calculated control-input sequence $u[k]$ is applied into the system as the control-input at the kth time-slot. At every time slot, the MPC optimization is solved and only the first element of the calculated control-input sequence is utilized.

III. PROBLEM FORMULATION

The aim of this work is to achieve a reliable WNCS considering the features of wireless communication. From the wireless communication perspective, the transmission powers to the feedforward and feedback channels should be efficiently allocated under a limited transmission power constraint. From the control system perspective, the control law (input) should be designed considering the reliability of the feedforward and feedback channels. Let P_T be the total transmitting power. Thus, the transmit powers of feedforward and feedback channels at the kth time-slot are given by $P_c[k] = (1 - \alpha[k])P_T$ and $P_p[k] = \alpha[k]P_T$ with the power allocation factor $\alpha[k]$ $(0 \leq \alpha[k] \leq 1)$. If the transmission rates of the feedforward and feedback channels (R_c and R_p) and average noise powers (N_c and N_p) are given, the outage probabilities become the function of the power allocation factor $\alpha[k]$, that is, $p_{cp}[k] = f_{cp}(\alpha[k])$, $p_{pc}[k] = f_{pc}(\alpha[k])$. This work tries to set optimum power allocation factor $\alpha[k]$ considering the control-state as well as the given communication parameters (i.e., P_T, R_c, R_p, N_c, and N_p).

Next, let us consider the impacts of communication errors at the feedforward and/or feedback channels on the control system. Depending on the communication result at the feedforward channel, the control-state can be given by

$$x[k+1] = \begin{cases} Ax[k] + Bu[k] & \text{with a prob. of } (1 - p_{cp}[k]) \\ Ax[k] & \text{with a prob. of } p_{cp}[k]. \end{cases} \tag{14}$$

This work assumes that the controlled plant applies not a hold-input scheme, but a zero-input scheme where the communication error occurs at the plant. A suggestion about which scheme is better can be seen in [4], [29]. In the feedback channel, the measured state is transmitted, then the observer tries to estimate the control-state from the received signal and the previously estimated state as

$$\tilde{x}[k+1] = \begin{cases} x[k+1] & \text{with a prob. of } (1 - p_{pc}[k]) \\ \tilde{x}[k+1|k] & \text{with a prob. of } p_{pc}[k] \end{cases} \tag{15}$$

In the case where the observer could successfully receive the signal, it can get a real control-state because neither disturbance at the plant nor measurement error at the sensor is assumed. In the case when the observer failed to receive the signal, the observer needs to estimate the control-state with the information at the previous time-slot. The estimation method at the observer should be changed corresponding to the applied communication protocol. If the acknowledgement-based communication protocol (TPC) is applied, in which the feedback information about successful or unsuccessful packet delivery at the receiver (ACK/NACK signals) is acknowledged to the sender within the same sampling time period, the estimation result at the observer can be given by

$$\tilde{x}[k+1|k] = \begin{cases} Ax[k] + Bu[k], & \text{when ACK is received} \\ Ax[k], & \text{when NACK is received.} \end{cases} \tag{16}$$

This work assumes that the sender can ideally receive ACK/NACK signals, (i.e., error-free). Thus, if the initial control-state is known at the controller side, the observer can ideally estimate the control-state regardless of the communication results at the feedback channel.

Next, let us consider the case with UDP which has no ACK/NACK signals.[1] Different from the case with TCP, if the observer failed to receive the signal from the sensor, it resorts to use the estimation value calculated with the information at the previous time-slot, as

$$\tilde{x}[k+1|k] = \mathbb{E}\left[x\left[k+1|k\right]\right] = A\tilde{x}[k] + (1-p_{cp}[k])Bu[k]. \tag{17}$$

Let $e[k]$ be the error between the estimation result and real control-state at the kth time-slot, that is, $e[k] = \tilde{x}[k] - x[k] \in \mathbb{R}^{N_x}$. With (14) and (17), the estimation error corresponding to the communication results at the feedforward and feedback channels can be calculated as

$$e[k+1] = \begin{cases} 0 \quad \text{with a prob. of } (1-p_{pc}[k]), \\ Ae[k] - p_{cp}[k]Bu[k] \\ \quad \text{with a prob. of } (1-p_{cp}[k])p_{pc}[k], \\ Ae[k] + (1-p_{cp}[k])Bu[k] \\ \quad \text{with a prob. of } p_{cp}[k]p_{pc}[k]. \end{cases} \tag{18}$$

It is obvious that the estimation error at the observer depends on the communication results of both feedforward and feedback channels, the control-input, and the previous estimation error. As a result, the calculation of control-input also depends on the control-input at the previous time-slots, which means that the separation principle does not hold in the UDP-based WNCS [4]. It is important to note that the communication-error (outage) probabilities $p_{cp}[k]$ and $p_{pc}[k]$ are controllable by appropriately setting the transmission power.

Considering the above circumstance, the goal of this paper is to provide an optimal power allocation and the corresponding control-input considering the (estimated) control-state for the TCP or UDP-based WNCS, which is defined as

$$[u[k], \alpha[k]] = \arg\min J_k^{\text{Prot}}, \tag{19}$$

$$J_k^{\text{Prot}} = f_c^{\text{Prot}}\left(\alpha[k], u[k], \cdots, u[k+N], \tilde{x}[k]\right), \tag{20}$$

$$s.t.,\ P_c[k] + P_p[k] \le P_T. \tag{21}$$

(20) is the cost function of the power allocation factor, control-inputs within the prediction horizon N, and the estimated control-state for solving the MPC-based optimization problem, which depends on the applied communication protocol (Prot $\in$ {TCP, UDP}). Therefore, we should first define the cost function corresponding to the applied communication protocol and then provide optimum control-input and power-allocation.

IV. JOINT OPTIMIZATION OF POWER ALLOCATION AND CONTROL-INPUT

This section provides two types of joint optimization methods which correspond to the applied communication protocol, (i.e., TCP or UDP). It is emphasized that the uncertainties caused by the communication error at the feedforward and/or feedback channels are controllable by adopting appropriate power allocation. Thus, this joint optimization can be considered as the cross-layer optimization between the communication and control layers. Some works, (e.g., [21]–[26]), have proposed some MPC based optimization methods for the case with additive/multiplicative stochastic uncertainties caused by the exogenous disturbance and/or model mismatch. Unlike these works, this section will focus on the probabilistic uncertainty caused by the communication errors at the feedforward and/or feedback channels and provide an optimum power allocation as well as the control-input corresponding to the type of communication protocol.

A. JOINT OPTIMIZATION FOR TCP-BASED WNCS

Proposition 1: (Power Allocation for TCP-based WNCS) The optimum power allocation factor α is always 0, that is, all transmission power should be allocated to the feedforward channel (from controller to plant).

Regardless of the communication results in the feedback channel, the observer can ideally estimate the control-state by virtue of ACK/NACK signaling as seen in (16). This means that TCP-based WNCS does not need the feedback signaling from the plant because neither the disturbance nor measurement (including quantization) error is assumed in this work. It is important to note that if we consider such an uncertainty at the controller side including the communication error of ACK/NACK signals in the feedforward channel, the communication of feedback channel is necessary for realizing a reliable WNCS.

[1] From the communication viewpoint, UDP cam be implemented more simply than TCP. This work assumes that the sampling time-period of both protocols is identical, even though UDP do not need the ACK/NACK signaling and thus can be implemented with shorter sampling time-period than TCP.

Theorem 1: (MPC for TCP-based WNCS) The optimum control-input for the TCP-based WNCS can be given by

$$u^{\mathrm{opt,TCP}}[k] = \left(\mathbf{U}^{\mathrm{opt,TCP}}\right)_1, \tag{22}$$

$$\mathbf{U}^{\mathrm{opt,TCP}} = \arg\min J_k^{\mathrm{TCP}}, \tag{23}$$

$$\begin{aligned} J_k^{\mathrm{TCP}}(\alpha, \mathbf{U}) &= \mathbb{E}\left[\mathbf{X}^T \bar{Q}\mathbf{X} + \mathbf{U}^T \bar{R}\mathbf{U}\right] \\ &= \mathbb{E}[\mathbf{X}]^T \bar{Q}\mathbb{E}[\mathbf{X}] + \mathbf{U}^T \bar{R}\mathbf{U} \\ &= \mathbf{U}^T\left(\bar{R} + \mathbf{B}'^T \bar{Q}\mathbf{B}'\right)\mathbf{U} + 2\,x[k]^T \mathbf{A}^T \bar{Q}\mathbf{B}'\mathbf{U} \\ &\quad + x[k]^T \mathbf{A}^T \bar{Q}\mathbf{A}x[k], \end{aligned} \tag{24}$$

where

$$\mathbf{B}' = (1 - p_{cp})\mathbf{B}. \tag{25}$$

Similar to the conventional MPC optimization, (23) can be solved with QP problem.

Proof: Although the estimated control-state has no uncertainty, the predictive control-state has uncertainty caused by the communication error at the feedforward channel. Thus, the expected control-state can be calculated as

$$\begin{aligned} \mathbb{E}[x[k+1]] &= Ax[k] + (1 - p_{cp}[k])Bu[k], \\ \mathbb{E}[x[k+2]] &= A\mathbb{E}[x[k+1]] + (1 - p_{cp}[k])Bu[k+1] \\ &= A^2 x[k] + A(1 - p_{cp}[k])Bu[k] \\ &\quad + (1 - p_{cp}[k])Bu[k+1], \\ &\ \vdots \\ \mathbb{E}[x[k+N]] &= A^N x[k] + A^{N-1}(1 - p_{cp}[k])Bu[k] + \cdots \\ &\quad + (1 - p_{cp}[k])Bu[k+N]. \end{aligned} \tag{26}$$

(26) can be rewritten the matrix-form as

$$\begin{aligned} \mathbb{E}\left[\begin{bmatrix} x[k+1] \\ x[k+2] \\ \vdots \\ x[k+N] \end{bmatrix}\right] &= \mathbb{E}[\mathbf{X}] = \mathbf{A}x[k] + (1 - p_{cp})\mathbf{B}\mathbf{U} \\ &= \mathbf{A}x[k] + \mathbf{B}'\mathbf{U}. \end{aligned} \tag{27}$$

By using the expected control-state given by (27), MPC optimization can be reformulated as (24). This implies that the evaluation function J_k^{TCP} monotonically decreases as the outage probability of feedforward channel p_{cp} becomes lower regardless of p_{pc}, that is, the power-allocation factor α becomes less. As mention above, in the case with TCP, the observer can get real control-state without the feedback from the plant, which results that $\alpha = 0$ ($P_c = P_T, P_p = 0$) is always optimum. ■

B. JOINT OPTIMIZATION FOR UDP-BASED WNCS

Different from the case of TCP-based WNCS, the observer in UDP-based WNCS cannot get the information whether the control-input could be successfully received at the plant or not, and thus it needs to estimate the state of plant from the received signal through the feedback channel. Only if the observer can successfully receive the signal from sensor, its estimation value becomes true. Otherwise, in the case when the observer failed to receive the signal, the output of observer is the estimation value calculated with the estimated result at the previous time, as seen in (17).

Here, we consider the calculation of MPC based optimization at the kth time slot. The initial state for MPC optimization can be given by $\tilde{x}[k] = x[k] + e[k]$, where $e[k]$ depends on the communication results of the feedback channel at the previous time-slots. Obviously, if the observer successfully received the signal from the sensor at the kth time-slot and then got the real control-state, $e[k]$ becomes 0 and thus the true control-state can be applied into MPC optimization as the initial value i.e., $\tilde{x}[k] = x[k]$. On the other hand, if the observer failed to receive, the estimated control-state with the uncertainty is applied to MPC optimization. Let $\tilde{\mathbf{X}}$ be the matrix form of the estimated control-state for N time-slot horizon and defined as

$$\underbrace{\begin{bmatrix} \tilde{x}[k+1] \\ \tilde{x}[k+2] \\ \vdots \\ \tilde{x}[k+N] \end{bmatrix}}_{\triangleq \tilde{\mathbf{X}}} = \underbrace{\begin{bmatrix} x[k+1] \\ x[k+2] \\ \vdots \\ x[k+N] \end{bmatrix}}_{\triangleq \mathbf{X}} + \underbrace{\begin{bmatrix} e[k+1] \\ e[k+2] \\ \vdots \\ e[k+N] \end{bmatrix}}_{\triangleq \mathbf{E}} \tag{28}$$

where $\mathbf{E}$ is the error (uncertainty) matrix and consists of the initial error $e[k]$ and the error probabilities in both feedforward and feedback channels as seen in (18).

Theorem 2: The joint optimization of power allocation factor α and control-input for UDP-based WNCS can be given by

$$\left[\mathbf{U}_{\alpha^{\mathrm{opt}}}^{\mathrm{opt}}[k], \alpha^{\mathrm{opt}}[k]\right] = \arg\min_{\alpha \in S_\alpha} J_k^{\mathrm{UDP}}\left(\alpha, \mathbf{U}_\alpha^{\mathrm{opt}}[k]\right), \tag{29}$$

$$u^{\mathrm{opt}}[k] = \left(\mathbf{U}_{\alpha^{\mathrm{opt}}}^{\mathrm{opt}}[k]\right)_1, \tag{30}$$

where $J_k^{\mathrm{UDP}}(\alpha, \mathbf{U}[k])$ is the modified cost function of both power allocation factor α and control-input sequence $\mathbf{U}[k]$, S_α is a candidate set of possible allocation factor ($S_\alpha = \{\alpha_1, \alpha_2, \cdots, \alpha_{n_\alpha}\}$, $(0 \le \alpha_n \le 1)$), and $\mathbf{U}_\alpha^{\mathrm{opt}}[k]$ is the calculated control-input of length $n_u N$ with MPC optimization, which is optimum control-input for the case with power allocation factor α. The optimum control-input sequence in the case with power allocation factor α can be calculated as

$$\mathbf{U}_\alpha^{\mathrm{opt}}[k] = \arg\min J_k^{\mathrm{UDP}}(\alpha, \mathbf{U}[k]), \tag{31}$$

where $J_k^{\mathrm{UDP}}(\alpha, \mathbf{U}[k])$ is the modified cost function with (24) and (28) and defined as

$$\begin{aligned} J_k^{\mathrm{UDP}}(\alpha, \mathbf{U}[k]) &= \mathbb{E}\left[\tilde{\mathbf{X}}^T \bar{Q}\tilde{\mathbf{X}} + \mathbf{U}^T \bar{R}\mathbf{U}\right] \\ &= \mathbb{E}\left[(\mathbf{X} + \mathbf{E})^T \bar{Q}(\mathbf{X} + \mathbf{E}) + \mathbf{U}^T \bar{R}\mathbf{U}\right] \\ &\triangleq \mathbb{E}\left[\mathbf{X}^T \bar{Q}\mathbf{X} + \mathbf{U}^T \bar{R}\mathbf{U}\right] + \lambda\mathbb{E}\left[\mathbf{E}^T \bar{Q}\mathbf{E}\right] \end{aligned} \tag{32}$$

where λ is the weighting parameter.

Proof: Giving α, the outage probabilities of feedforward and feedback channels (p_{cp} and p_{pc}) can be calculated as seen in (3) and (4). The first term of (32) is identical to

TABLE 1. The expected square-estimation-error in the case of UDP-based WNCS.

Probability	$\tilde{x}[k+1] =$	$x[k+1] =$	$e[k+1] =$
$(1-p_{cp})(1-p_{pc})$	$Ax[k] + Bu[k]$	$Ax[k] + Bu[k]$	0
$p_{cp}(1-p_{pc})$	$Ax[k]$	$Ax[k]$	0
$(1-p_{cp})p_{pc}$	$A\tilde{x}[k] + (1-p_{cp})Bu[k]$	$Ax[k] + Bu[k]$	$Ae[k] - p_{cp}Bu[k]$
$p_{cp}p_{pc}$	$A\tilde{x}[k] + (1-p_{cp})Bu[k]$	$Ax[k]$	$Ae[k] + (1-p_{cp})Bu[k]$
$\mathbb{E}[e[k+1]^T Qe[k+1]] = (Ae[k])^T Q(Ae[k]) + p_{cp}(1-p_{cp})p_{pc}(Bu[k])^T Q(Bu[k])$			
Probability	$\tilde{x}[k+2] =$	$x[k+2] =$	$e[k+2] =$
$(1-p_{cp})(1-p_{pc})$	$Ax[k+1] + Bu[k+1]$	$Ax[k+1] + Bu[k+1]$	0
$p_{cp}(1-p_{pc})$	$Ax[k+1]$	$Ax[k+1]$	0
$(1-p_{cp})p_{pc}$	$A\tilde{x}[k+1] + (1-p_{cp})Bu[k+1]$	$Ax[k+1] + Bu[k+1]$	$Ae[k+1] - p_{cp}Bu[k+1]$
$p_{cp}p_{pc}$	$A\tilde{x}[k+1] + (1-p_{cp})Bu[k+1]$	$Ax[k+1]$	$Ae[k+1] + (1-p_{cp})Bu[k+1]$
$\mathbb{E}[e[t]^T Qe[t]] = (Ae[k+1])^T Q(Ae[k+1]) + p_{cp}(1-p_{cp})p_{pc}(Bu[k+1])^T Q(Bu[k+1])$			

the cost function of TCP-based WNCS given by (24), which depends only on the outage probability of feedforward channel (p_{cp}). The second term is the expected squared error of the control-state estimated at the controller side, which depends on the outage probabilities of both channels (p_{cp} and p_{pc}). Thus, the weighting parameter λ can manage the capabilities of both MPC based control and the accuracy of estimation at the controller side.

Next, we focus on $\mathbb{E}\left[\mathbf{E}^T \bar{\mathbf{Q}}\mathbf{E}\right]$ in (32). As seen in (18), the estimation error at the $(k+1)$th time-slot depends on the communication results of the feedforward and feedback channels. Then, its expected value is given by

$$\begin{aligned}\mathbb{E}\left[e[k+1]\right] &= \left(1-p_{cp}[k]\right)p_{pc}[k]\left(Ae[k] - p_{cp}[k]Bu[k]\right)\\ &\quad + p_{cp}[k]p_{pc}[k]\left(Ae[k] + \left(1-p_{cp}[k]\right)Bu[k]\right)\\ &= p_{pc}A\mathbb{E}\left[e[k]\right] = p_{pc}^2 A^2 \mathbb{E}\left[e[k-1]\right]\\ &= \cdots, = p_{pc}^{k+1}A^{k+1}\mathbb{E}\left[e[0]\right] = 0. \qquad (33)\end{aligned}$$

On receiving the signal from sensor, the observer gets the estimation value $\tilde{x}[k+1]$. As mentioned above, when the observer successfully receives the signal, the estimated value is the true control-state. Otherwise, the estimated value is the expected value calculated at the previous (kth) time slot. The errors at the future time-slots can be inductively calculated as shown in Table 1. Then, the nth element of $\mathbb{E}\left[\mathbf{E}^T \bar{\mathbf{Q}}\mathbf{E}\right]$ can be given by

$$\begin{aligned}&\mathbb{E}\left[e[k+n]^T Qe[k+n]\right]\\ &= (1-p_{cp})p_{cp}p_{pc}u^T[k-n-1]B^T QBu[k-n-1]\\ &\quad + (1-p_{cp})p_{cp}p_{pc}^2 u^T[k-n-2]B^T A^T QABu[k-n-2]\\ &\qquad \vdots\\ &\quad + (1-p_{cp})p_{cp}p_{pc}^n u^T[k]B^T\left(A^{n-1}\right)^T QA^{n-1}Bu[k]\\ &\quad + p_{pc}^n e^T[k]\left(A^n\right)^T Q\left(A^n\right)e[k]. \qquad (34)\end{aligned}$$

Using (34), $\mathbb{E}\left[\mathbf{E}^T \bar{Q}\mathbf{E}\right]$ can be rewritten to the matrix form as

$$\begin{aligned}\mathbb{E}\left[\mathbf{E}^T \bar{Q}\mathbf{E}\right] &= \mathbb{E}\left[\begin{bmatrix} e^T[k+1]Qe[k+1]\\ e^T[k+2]Qe[k+2]\\ \vdots\\ e^T[k+N]Pe[k+N]\end{bmatrix}\right]\\ &= \mathbf{U}^T \bar{Q}_e \mathbf{U} + \epsilon, \qquad (35)\end{aligned}$$

where $\bar{Q}_e$ is a lower triangular matrix given by

$$\bar{Q}_e = (1-p_{cp})p_{cp}\begin{bmatrix} Qe_{1,1} & \cdots & Qe_{1,N}\\ \vdots & \ddots & \vdots\\ Qe_{N,1} & \cdots & Qe_{N,N}\end{bmatrix} \qquad (36)$$

$$Qe_{i,j} = \begin{cases} 0, & i < j\\ p_{pc}^{i-j+1}B^T\left(A^{i-j}\right)^T Q\left(A^{i-j}\right)B, & i \geq j,\end{cases} \qquad (37)$$

and ϵ is the square error factor calculated only with the initial estimation error in MPC optimization and expressed as

$$\epsilon = \mathbb{E}\left[e^T[k]\left(\sum_{n=1}^{N} p_{pc}^n\left(A^n\right)^T QA^n\right)e[k]\right]. \qquad (38)$$

Note that, since $e[k]$ is determined by the error pattern at the previous time-slots, the controller needs to stock all error patterns and corresponding probabilities over past consecutive error duration in the feedback channel. ■

Substituting (35) into (32), the cost function can be reformulated as

$$\begin{aligned}J_k^{\mathrm{UDP}}(\alpha, \mathbf{U}) &= \mathbf{U}^T\left(\bar{R} + \mathbf{B}'^T \bar{Q}\mathbf{B}' + \lambda\bar{Q}_e\right)\mathbf{U}\\ &\quad + 2\,x[k]^T \mathbf{A}^T \bar{Q}\mathbf{B}'\mathbf{U} + x[k]^T \mathbf{A}^T \bar{Q}\mathbf{A}x[k] + \epsilon. \qquad (39)\end{aligned}$$

Since ϵ is independent to the control-input (sequence) and (39) is quadratic, this can be solved with QP.

V. NUMERICAL EXAMPLES

The parameters used in the numerical evaluations are given by as follows.

$$\begin{aligned}A &= \begin{bmatrix} 1.19 & 0.08\\ 0.22 & 0.89\end{bmatrix}, \quad B = \begin{bmatrix} 0.75\\ 0.9\end{bmatrix}\\ x[0] &= \begin{bmatrix} 50\\ -50\end{bmatrix}, \quad Q = P = R = \begin{bmatrix} 1 & 0\\ 0 & 1\end{bmatrix} \qquad (40)\end{aligned}$$

The matrix A is unstable, that is, composed of one stable and unstable eigenvalues $\mathrm{eig}(A) = (1.2402, 0.8398)$. It is easy to verify that the pair (A, B) is controllable. Initial and target control-states are set as $[50, -50]^T$ and $[0, 0]^T$, respectively. The weighting matrices for MPC optimization (i.e., P, Q, and R) are assumed to be identity matrices. To evaluate the quality of control, the mean square error (MSE) defined as $\mathbb{E}\left[|x[k]|^2\right]$ is used. We consider the MPC optimization defined in (7) and (8) as the conventional scheme, which does not consider the communication errors. We assume that the noise powers at the controller and plant sides are the same, (i.e., $N_p = N_c$).

A. PERFORMANCE EVALUATION IN TCP-BASED WNCS

From Proposition 1, the power allocation factor α is always set as 0, that is, $P_c = P_T$, $P_p = 0$. Thus, we only consider the communication error at the feedforward channel and define the signal-to-noise ratio (SNR) as $10 \log_{10} P_c/N_p$ in dB. Also, we assume that the transmission rate in the feedforward channel is given by $R_c = 5$ bps/Hz and SNR is 20 dB. In this case, from (3), the outage probabilities of feedforward and feedback channels can be calculated as $p_{cp} = 0.2666$ and $p_{pc} = 1$, respectively. It is a well-known fact that the longer predictive period can achieve better control performance, whereas the computational burden for the MPC optimization exponentially increases in proportion to the length of predictive period N. From the comparison between the conventional MPC and the proposed scheme given by Theorem 1 (as seen in Fig. 2), the proposed MPC can enhance the MSE performance regardless of the predictive period. Thus, the proposed MPC can more efficiently work than the conventional MPC. The performance gap between $N = 8$ and $N = 10$ is smaller than the one between $N = 5$ and $N = 8$ as well as between $N = 3$ and $N = 5$. Considering the trade-off between performance enhancement and computational complexity, we use $N = 8$ hereinafter.

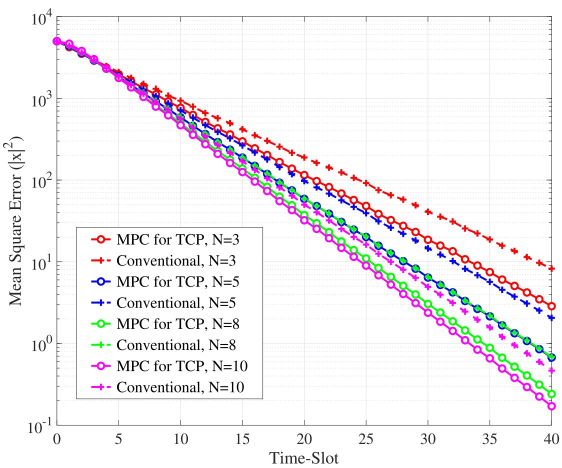

FIGURE 2. Impact of the length of predictive period (N) and performance comparison between the proposed MPC for TCP-based WNCS and the conventional MPC ($R_c = 5$ bps/Hz, SNR= 20 dB).

B. PERFORMANCE EVALUATION IN UDP-BASED WNCS

In the UDP-based WNCS, the controller side needs to estimate the control-sate of the plant and thus the quality of control depends on the communication quality of both feedback and feedforward channels. Fig. 3 shows the state trajectory and its corresponding power allocation factor α in the case where the transmission rates at the feedforward and feedback channels are 5 ($R_c = R_p = 5$ bps/Hz), SNR= $10 \log_{10}(P_c + P_p)/(N_p + N_c) = 20$ dB, the predictive period for MPC optimization is 8 ($N = 8$), the set of candidate for power allocation is $S_\alpha = \{0, 0.05, 0.1, \cdots, 1\}$ ($\alpha \in S_\alpha$), and the weighting parameter $\lambda = 10$. If the power allocation factor is given by $\alpha = 0.5$, the outage probabilities of feedforward and feedback channels are identical and calculated as $p_{cp} = p_{pc} = 0.2666$. The blue and red dotted lines in Fig. 3 show the error events at the feedforward and feedback channels, respectively. It is seen from the upper part of Fig. 3 that the power allocation factor often has a value of 0.45 (the transmission power for the feedforward channel is slightly higher than the one for feedback channel). However, when the communication error at the feedback channel occurs, the power allocation factor has a tendency to become higher than 0.45. This is because the system tries to suppress the estimation error at the controller side.

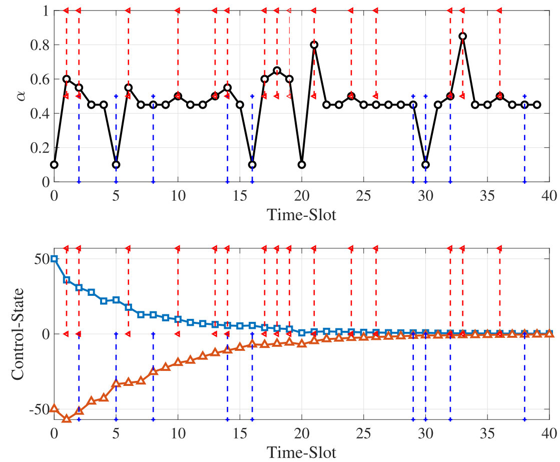

FIGURE 3. State trajectory and its corresponding power allocation factor α in the case where $R_c = R_p = 5$ bps/Hz, SNR= 20 dB, and $\lambda = 10$, Blue and red dotted lines show the communication error event at the feedforward and feedback channels, respectively.

Fig. 4 shows the average MSE performances of the conventional and the proposed MPC in the case where SNR= 20 dB, $R_c = R_p = 5$ bps/Hz, $N = 8$, $\lambda = 1, 10, 100, 1000$, and the number of trials is 10000. We also illustrate the performances of the proposed MPC designed for TCP-based WNCS (Theorem 1) in the cases with $\alpha = 0.5, 1.0$ and the conventional MPC. The MPC optimization for TCP with $\alpha = 1$ can efficiently work till time-slot ($k \leq 6$), whereas it cannot work at the region of $k > 6$. Since $\alpha = 1$, the gap between estimated control-state at the controller and real control-state becomes larger in proportion to the time-slot k. On the other hand, in the case with $\alpha = 0.5$, the MPC optimization for TCP-based WNCS can work and achieve better performance than the conventional MPC since it considers the error probability of the feedforward channel and can use the feedback information for the estimation of control-state. The MPC optimization for UDP-based WNCS can further improve the performance since it can appropriately change the transmission power corresponding to the control-state and estimation accuracy at the controller side.

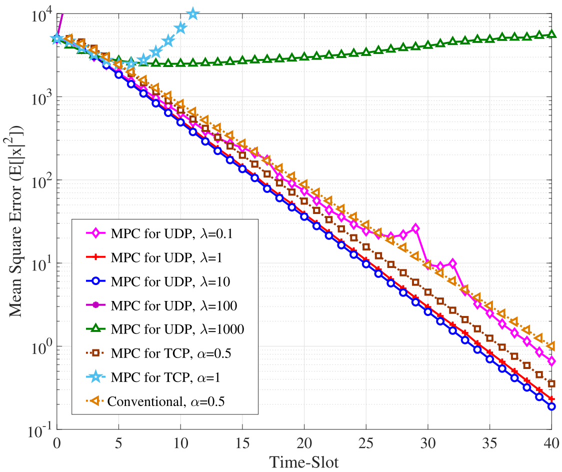

FIGURE 4. MSE performances of the proposed MPC based joint optimization in the UDP-based WNCS with SNR= 20 dB, $R_c = R_p = 5$, and $N = 8$.

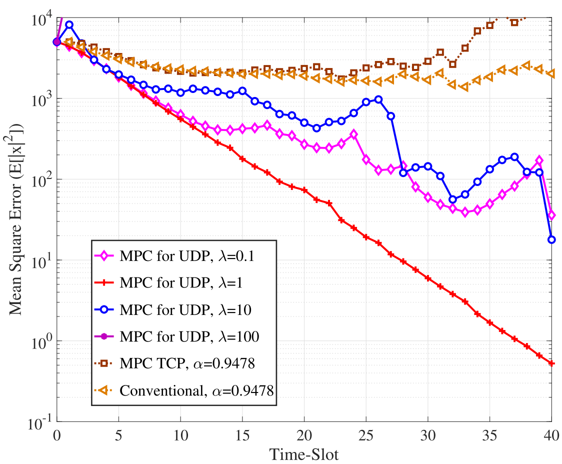

FIGURE 5. MSE performances of the proposed MPC based joint optimization in the UDP-based WNCS with SNR= 20 dB, $R_c = 3$, $R_p = 7$, and $N = 8$.

The MPC optimization for UDP-based WNCS with $\lambda = 10$ can achieve the best performance but the ones with $\lambda = 100$ and 1000 cannot efficiently work. Therefore, the parameter λ should be carefully chosen.

Figs. 5 and 6 show the MSE performances in the cases where the transmission rates at the feedforward and feedback channels are given by $R_c = 3$, and $R_p = 7$ bps/Hz and SNR= 20 and 25 dB, respectively. From the communication theory viewpoint, the power allocation factor α should be set in order for individual outage probabilities to be identical, that is, $p_{pc} = p_{cp}$, because $\min\max(p_{pc}, p_{cp})$ subject to the limited transmission power is equal to the case that $p_{pc} = p_{cp}$. Thus, under the condition that $R_c = 3$ and $R_p = 7$ bps/Hz, the power allocation factor should be set as $\alpha = 0.9478$. As a result, the outage probabilities in the cases of SNR= 20 and 25 can be calculated as $p_{cp} = p_{pc} = 0.488$ and $p_{cp} = p_{pc} = 0.191$, respectively. The proposed MPC optimization for UDP-based WNCS adaptively changes the power allocation factor considering the expected cost for control and expected estimation-accuracy as seen in (32). From Fig. 5, the MPC optimization for TCP-based WNCS with $\alpha = 0.9478$ and the conventional MPC with $\alpha = 0.9478$ cannot work, whereas the MPC optimization for UDP-based WNCS with $\lambda = 0.1$, 1, and 10 can work. In particular, the MPC optimization for UDP-based WNCS with $\lambda = 1$ can significantly improve the MSE performance. However, if an inappropriate parameter (e.g., $\lambda = 100$) is applied, the proposed MPC optimization for UDP-based WNCS cannot work.

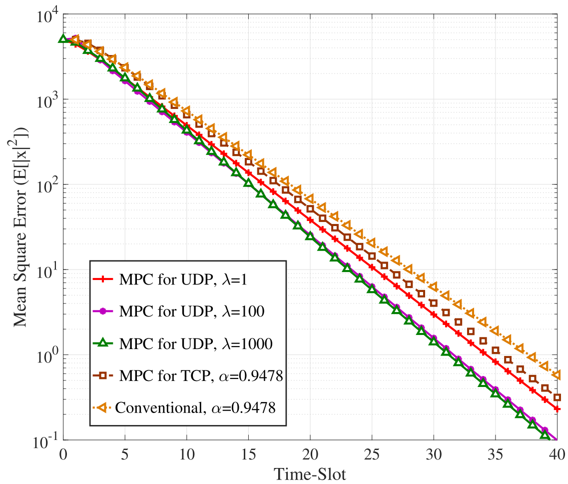

FIGURE 6. MSE performances of the proposed MPC based joint optimization in the UDP-based WNCS with SNR= 25 dB, $R_c = 3$, $R_p = 7$, and $N = 8$.

Fig. 6 shows the case with SNR= 25 dB where the communication links can be built more reliable than the case with SNR= 20 dB. Since the MSE performances of the MPC optimization for UDP with $\lambda = 0.1, 1, 10$ are almost the same, we only show the case with $\lambda = 1$. The MPC optimization for UDP-based WNCS with $\lambda = 1000$ can achieve the best performance. Compared to the case of SNR= 20, the optimum parameter λ is larger. This is because, in the WNCS with reliable communication networks, the accuracy of estimated control-state is more important factor than the control cost, as seen in Theorem 2.

VI. CONCLUSION

This paper has provided the joint optimization of transmission power and control-input corresponding to the applied communication protocol. The proposed algorithm is designed based on the cross-layer optimization between communication and control layers. Simulation results show that the proposed method can efficiently allocate the transmission power considering the control-state and the accuracy of estimation and thus can enhance the quality of control.

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