Optimal LQG Control under Delay-dependent Costly Information

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Abstract— In the design of closed-loop networked control systems (NCSs), induced transmission delay between sensors and the control station is an often-present issue which compromises control performance and may even cause instability. A very relevant scenario in which network-induced delay needs to be investigated is costly usage of communication resources. More precisely, advanced communication technologies, e.g. 5G, are capable of offering latency-varying information exchange for different prices. Therefore, induced delay becomes a decision variable. It is then the matter of decision maker’s willingness to either pay the required cost to have low-latency access to the communication resource, or delay the access at a reduced price. In this article, we consider optimal price-based bi-variable decision making problem for single-loop NCS with a stochastic linear time-invariant system. Assuming that communication incurs cost such that transmission with shorter delay is more costly, a decision maker determines the switching strategy between communication links of different delays such that an optimal balance between the control performance and the communication cost is maintained. In this article, we show that, under mild assumptions on the available information for decision makers, the separation property holds between the optimal link selecting and control policies. As the cost function is decomposable, the optimal policies are efficiently computed.

I. INTRODUCTION

In the design of closed-loop NCSs where information is exchanged between sensors, controller and actuator over a limited-resource communication network, induced transmission delay plays a key role in characterizing control performance and stability properties [1], [2]. Day-by-day increase of data volume that needs to be exchanged urges access to fast and low-error communication infrastructure to support the stringent real-time requirements of such systems. This, however, imposes higher communication and computation costs, resulting in reconsideration of employing time-based sampling techniques with equidistant fixed temporal durations. Various approaches are developed to coordinate data exchange in NCSs with the aim of reducing the total sampling and communication rate. Effective techniques such as event-based sampling, scheduling, and network pricing are introduced leading to the reduction of communication and computational costs by restricting unnecessary data sampling. Having intermittent sampling, delay is induced in various parts of the networked system which may degrade control performance. Hence, such decision makers need to be carefully designed in order to preserve stability as well as providing required quality-of-control (QoC) guarantees.

Event-based control introduced as a beneficial design framework to coordinate sampling of signals based on some urgency metrics, e.g. an action is executed only when some pre-defined events are triggered [3]. This idea received substantial attention and is further developed as a technique capable of significantly reducing sampling rate while preserving the required QoC [4]–[8]. The mentioned works, among many more, consider sporadic data sampling governed by real-time conditions of the control systems or the communication medium. Synthesis of optimal event-based strategies in NCSs is also addressed [9]–[11].

Data scheduling is employed by communication theorists for decades as an effective resource management technique [12], [13]. By emerging NCSs as integration of multiple control systems supported by communication networks, cross-layer scheduling attracted more attentions. The reason is scheduling induces delay and affects NCS stability and QoC, hence, scheduling approaches that take into account real-time conditions of control systems become popular [8], [14], [15].

Designing price mechanisms for multi-user networks, to guarantee quality-of-service (QoS) is popular in communication [16], [17]. In these works the goal is often set to maximize the QoS, which is a network-dependent utility expressed often in form of effective bandwidth requirements. In NCSs, however, QoC is of interest which additionally takes into account users’ dynamics. Optimal communication pricing aiming at maximizing the QoC in NCSs has received less attention with a few exceptions, e.g. [18], [19].

In those mentioned works, delay is considered an inevitable network-induced phenomena resulting from the employed sporadic sampling mechanisms. Novel communication technologies, e.g. 5G, offer not only “bandwidth” as the resource to pay for, but also real-time “latency”. Users can decide to pay a higher price for lower latency or to delay data exchange at a reduced price. In such scenarios, the resulting induced delay plays as an explicit decision variable, i.e., users can optimize their utilities versus the communication price. In this article, we take the first steps in this direction by addressing the problem of joint optimal control and
delay-dependent switching policies for a single-loop NCS with costly communication. The switching law determines the length of delay associated with the data sent over the network. We assume that every transmission incurs a cost determined by the associated delay, such that shorter delay incurs higher cost. Aggregating the LQG cost and delay-dependent communication cost over a finite horizon, we derive the optimal control and switching laws assuming that communication prices are known apriori. It is then shown that the optimal control and switching laws are separable in expectation, and thus can be computed offline. It guarantees the computational feasibility of our proposed approach.

II. PROBLEM FORMULATION

Consider an LTI controlled system, consisting of a physical plant $P$ and a controller $C$. The plant $P$ is described by

$$x_{k+1} = Ax_k + Bu_k + w_k$$

(1)

where $x_k \in \mathbb{R}^n$ is the system state, $u_k \in \mathbb{R}^m$ is the control signal executed at time $k$, and $w_k \in \mathbb{R}^n$ is the exogenous disturbance. The constant matrices $A \in \mathbb{R}^{n \times n}$, and $B \in \mathbb{R}^{n \times m}$ describe drift matrix, and input matrix, with the pair $(A, B)$ assumed to be controllable. The disturbance $w_k$ and the initial state $x_0$ are i.i.d. random variables with realizations $w_k \sim N(0, W)$, and $x_0 \sim N(0, \Sigma_0)$, where $W \succeq 0$ and $\Sigma_0 \succeq 0$ denoting the variances of the respective Gaussian distributions. For the purpose of simplicity, we assume that the sensor measurements are perfect copies of state values.

In this article we address a delay-dependent LQG problem. As shown in Fig. 1 there are $D$ number of links, each associated with a delay time $\{1, \ldots, D\}$. Selection of transmission link decides the arrival time instance of data at the controller, i.e., controller update may be delayed. Each link has a known cost of operation that increases as delay decreases. Note that, in the NCS scenario illustrated in Fig. 1 the control unit which determines the switching policy of transmission links is a separate decision making unit with specific information structure, and must be distinguished from the plant controller.

Recall that the optimal LQG control is a certainty equivalent control that uses state estimation based on regularly-sampled measurements. In this work, however, the arrival of measurements and consequently the estimation quality depends on the selected delay link. Thus, unlike standard optimal LQG where there is one controller that generates the control signal, here another control unit with an appropriate information structure exists and determines the optimal strategy to select the delay links. To take this into account, we first define the binary decision variable $\theta_k^i$ as follows:

$$\theta_k^i = \begin{cases} 1, & \text{at time } k \text{ link with } i \text{ step delay is selected} \\ 0, & \text{at time } k \text{ link with } i \text{ step delay is not selected} \end{cases}$$

Based on the above definition, if $\theta_k^i = 1$, the controller has access to system state $x_k$ at time-step $k+i$. We assume the possibility of selecting more than one links at each time, i.e.

$$\sum_{i=1}^{D} \theta_k^i \geq 1, \quad \forall k \in \{1, 2, \ldots\}$$

(2)

where, the finite variable $D \in \mathbb{N}$ denotes the maximum allowable delay. Each link with associated delay $i$ is assigned a price, denoted by $\lambda_i \in \mathbb{R}^+$, to be paid if it is selected for transmission. Hence, at each time $k$, the switching decision $\theta_k$, can be represented by a binary-valued vector as follows

$$\theta_k \triangleq [\theta_k^1, \ldots, \theta_k^D]^T.$$  (3)

The prices for each communication link $i \in \{1, \ldots, D\}$ are denoted by $\lambda_i$, and are fixed apriori with the following order:

$$\lambda_1 > \lambda_2 > \ldots > \lambda_D > 0.$$  

Remark 1: In this framework, a link with very large delay $D_{ol} \gg 1$ and cost $\lambda_{ol} = 0$ can be added such that a transmission becomes very unlikely. Theoretically, $D_{ol} \to \infty$, the system opts to be open-loop. In our scenario, however, system is forced to select at least one link, according to (2).

According to (3), the received state information at the controller at time-step $k$, denoted by $\mathcal{Y}_k$, is expressed as

$$\mathcal{Y}_k = \{\theta_k^1 x_{k-1}, \theta_k^2 x_{k-2}, \ldots, \theta_k^D x_{k-D}\}.$$  (4)

where, $\theta_k^i = \ldots = \theta_k^{D-1} = 1$, for all $i$ to represent equations compactly. The system possesses two decision makers; one decides the delay link via $\theta_k$, and one computes control signal $u_k$. To define the information set and the associated $\sigma$-algebra available to each decision maker, we first introduce two sets $\mathcal{Y}_k \triangleq \{\mathcal{Y}_0, \ldots, \mathcal{Y}_k\}$, and $\mathcal{U}_k \triangleq \{u_0, \ldots, u_k\}$, containing the received state information, and control signals, up to and including time $k$, respectively. We now define the information sets $\mathcal{I}_k$ and $\mathcal{I}_k$ at time $k$, respectively accessible for the switching and the plant controllers, as follows:

$$\mathcal{I}_k \triangleq \{\mathcal{Y}_0, U_{k-1}, \cup_{i=1}^{k-1} \{\theta_i\}\}, \quad \mathcal{I}_k \triangleq \{\mathcal{I}_k, \mathcal{Y}_k, \theta_k\}.$$  

At every time $k$, the control and delay switching strategies are measurable functions of the $\sigma$-algebras generated by $\mathcal{I}_k$, and $\mathcal{I}_k$, respectively, i.e., $u_k = g_k(\mathcal{I}_k)$, and $\theta_k = s_k(\mathcal{I}_k)$. The order of decision making in one cycle of sampling is as follows: $\ldots \to \mathcal{I}_k \to \theta_k \to \mathcal{I}_k \to u_k \to \mathcal{I}_{k+1} \to \ldots$. In general, the computation of the optimal control $u_k^*$ requires the knowledge of the optimal $\theta_k^*$. However, we show later that, under the introduced information structures, $\theta_k^*$ can be computed offline, and hence computation $u_k^*$ will not require on-line update about $\theta_k^*$. A possible implementation of this protocol is to send the preference of selecting the delay link to a
network manager (it is the communication service provider that offers different QoS (delay)) that, upon receiving the sensor data \(x_k\), selects the preferred transmission link.

The cost function, that is jointly minimized by the two decision variables \(g_k(\tilde{T}_k)\), and \(s_k(\tilde{I}_k)\), consists of an LQG part and communication cost. Within the finite horizon, the average cost function is stated by the following expectation

\[
J(u, \theta) = E \left[ \sum_{t=0}^{T-1} \left( x_t^T Q_1 x_t + u_t^T R u_t + \theta_t^T A \right) + x_T^T Q_2 x_T \right],
\]

where, \(A \triangleq [\lambda_1, \ldots, \lambda_D]^T\), \(Q_1 \succeq 0, Q_2 \succeq 0, \) and \(R > 0\).

III. OPTIMAL STRATEGIES FOR CONTROL & SWITCHING

The optimal control and switching strategies are the minimization of the latter average cost function, i.e.

\[
(u^*, \theta^*) = \arg\min_{u, \theta} J(u, \theta),
\]

where the average cost optimal value equals \(J^* = J(u^*, \theta^*)\). In the sequel, we show that the problem (5) is separable in its network manager (it is the communication service provider decision variables \(u^*\)), and the average cost optimal value equals \(J^*\). Moreover, we define the cost-to-go

\[
\pi_k = E \left[ \sum_{t=k+1}^{T} P_T \sum_{j=0}^{T-1} P_t \sum_{i=0}^{T-1} P_{i,j} e_i(\tilde{I}_{i,j}) \right],
\]

with, \(e_i = x_k - E[x_k|\tilde{I}_k]\), \(P_t = \frac{Q_1}{A^T (P_{k+1} + B R P_{k+1})^{-1} B^T P_{k+1}} A\), \(P_T = Q_2\).

Proof: The proof is presented in Appendix [VII-A].

From Theorem 1, \(g_k^*(\tilde{T}_k) = L_k E[x_k|\tilde{I}_k]\), with \(L_k\) independent of \(\theta\). This allows us to design the control law offline, while the estimator is \(\theta\)-dependent (Proposition 2). This is intuitive as \(\lambda_i\)'s are assumed to be state and time-independent. State and time dependency in prices is the subject of future work. For example when \(\lambda_i = x_i^T \mu_i x_k + \mu_i^2 x_k + \mu_i^3\), the Riccati equation of \(P_k\) in (6) will depend on the parameters \(\mu_i, \mu_i^2, \mu_i^3\). In this work, we restricted ourselves to state-independent, time-independent costs for the links.

B. OPTIMAL SWITCHING STRATEGY

Here we first show that the estimation at the controller is \(\theta\)-dependent. It results in \(e_k\) being also \(\theta\)-dependent, \(\forall k > 0\).

Proposition 2: The estimator dynamics is \(\theta\)-dependent s.t.

\[
\delta_k = E[x_k|\tilde{I}_k] = \sum_{i=1}^{\min(D, k+1)} b_{i,k} E[x_k|x_{k-i}, U_{k-1}],
\]

where, \(\forall k \geq 0, i \in \{1, \ldots, D\}\), \(b_{i,k} \in \{0, 1\}\). Moreover, \(\sum_{i=1}^{\min(D, k+1)} b_{i,k} = 1\), and if \(D > k\), then \(\sum_{i=k+1}^{D} b_{i,k} = 0\).

Proof: Proof is presented in Appendix [VII-B].

Defining \(\tau_k \triangleq \min\{D, k+1\}\), and initial condition \(e_0 = x_0 - E[x_0]\), and \(w_{-1} = e_0\) for notational convenience; and knowing the noise realizations \(\{w_{-1}, w_0, \ldots, w_{T-1}\}\) are mutually independent, it concludes from Proposition 2 that

\[
e_k = x_k - E[x_k|\tilde{I}_k] = \sum_{j=1}^{\tau_k} \sum_{i=1}^{\tau_k} b_{i,j} A^j w_{k-j-1},
\]

where, \(W_{-1} = E[e_0|e_{-1}^0] = \Sigma_0\), \(W_0 = W_1 = \cdots = W\), and \(c_{i,k} = \sum_{j=1}^{\tau_k} b_{i,j} A^j\). Having this, one can show

\[
V_k^* = \tilde{x}_k^T P_k \delta_k + tr(P_k M_k) + \sum_{t=k}^{T-1} tr(P_t M_t) + \sum_{t=k+1}^{T} tr(P_t W_t).
\]
Consequently, we can express $J_0^*$ as follows:

$$J_0^* = \min_{\theta_{[0,T-1]}} \sum_{t=0}^{T-1} \left[ \sum_{i=1}^{\gamma_t} c_i t r(\tilde{P}_t A_i^{1-T} W_t A_i^{1-1}) + \gamma_t^T \Lambda \right]$$

$$+ \tilde{x}_0 P \tilde{x}_0 + \sum_{t=1}^{T} tr(P_t W) + tr(M_0 P_0), \quad (12)$$

Let us define two vectors $\gamma_t$ and $r_t$, as in the following:

$$\gamma_t \triangleq [c_1 t, c_2 t, \ldots, c_{\gamma_t} t]^T,$$

$$r_t \triangleq [tr(P_t W), tr(\tilde{P}_t A_1^T W A_1), \ldots, tr(\tilde{P}_t A_D^{1-T} W A_D^{1-1})]^T.$$ 

Since the term $\tilde{x}_0 P \tilde{x}_0 + \sum_{t=1}^{T} tr(P_t W) + tr(M_0 P_0)$ in (12) is independent of $\theta_{[0,T-1]}$, minimizing (12) is equivalent to

$$J_0^* = \min_{\theta_{[0,T-1]}} \sum_{t=0}^{T-1} \left[ \gamma_t^T r_t + \theta_t^T \Lambda \right]. \quad (13)$$

After defining $\gamma(\gamma_t)_i$, to be the $i$-th component of the vector $\gamma_t$, the optimal strategy $\theta_{[0,T-1]}$ is the solution of the following mixed integer nonlinear programming (MINP):

$$\min_{\theta_{[0,T-1]}} \sum_{t=0}^{T-1} \left[ \theta_t^T A + \gamma_t r_t \right] \quad (14)$$

subject to

$$\gamma(\gamma_t)_i = \sum_{j=1}^{D} b_j t_j, \quad \sum_{i=1}^{D} \theta_i^T k_i \geq 1$$

$$b_{i,k} = \prod_{j=1}^{t_k} \prod_{j=1}^{d} (1 - \theta_{k,i}^T k_{i,d})(\gamma(\gamma_t)_i \theta_{k,i})$$

$$\sum_{i=1}^{\tau_k} b_{i,k} = 1, \quad \sum_{i=k+2}^{D} b_{i,k} = 0$$

$$b_{i,k} \in \{0,1\}, \quad \theta_{i} \in \{0,1\}, \quad \forall k \in [0,T-1], i \in [1,D],$$

Remark 3: The optimal switching strategy $\theta_{[0,T-1]}$ is independent of the noise realizations and can be solved offline. This result is analogous to the conclusions of [20], wherein the optimal sensor schedule for a delay-free open-loop control system with linear Gaussian-disturbed sensors is shown to be independent of the Gaussian noise realizations.

To significantly reduce the computational complexity of the MINP (14), we show that the derived MINP can be equivalently re-casted as a mixed integer linear program (MILP), by exploiting certain structure of the specific network setting. This will significantly reduce the computational burden as well as might provide a way to further relaxed it to a linear programming (LP) problem. For this, by replacing $\sum_{i=1}^{D} \theta_i^T k_i \geq 1$ with $\sum_{i=1}^{D} \theta_i^T k_i = 1$ enables us to replace $\gamma(\gamma_t)_i$ in (14) by $\sum_{i=1}^{D} \theta_i^T k_i$. Thus,

$$\min_{\theta_{[0,T-1]}} \sum_{t=0}^{T-1} \left[ \gamma_t^T A + \gamma_t r_t \right] \quad (15)$$

subject to

$$\gamma(\gamma_t)_i = \sum_{j=1}^{D} b_j t_j, \quad \sum_{i=1}^{D} \theta_i^T k_i = 1$$

$$b_{i,t} = \prod_{j=1}^{d} (1 - \theta_{i,t-d})(\sum_{i=1}^{T-1} \theta_{i,t-i})$$

$$\sum_{i=1}^{\tau_k} b_{i,t} = 1, \quad \sum_{i=t+2}^{D} b_{i,t} = 0$$

$$b_{i,t} \in \{0,1\}, \quad \theta_{i,t} \in \{0,1\}, \quad \forall t \in [0,T-1], i \in [1,D].$$

Clearly, due to the conversion of an inequality constraint to an equality constraint, every feasible solution of (15) is a feasible solution for (14), and moreover the optimal value for (15) is no less than that of (14). Therefore, we only need to show that an optimal solution for (14) is a feasible solution for (15). To show this, we first claim that every $\theta$ which is feasible for (14) but not for (15) (i.e., $\sum_{i=1}^{D} \theta_i^T k_i > 1$ for some $k$), there exists a $\theta$ which achieves a strictly lower cost than $\theta$. Let $1 \leq i_1 < i_2 < \ldots < i_m \leq D$ be the indices such that $\theta_{i_1}^T k_i = 1$. Now we construct a new $\theta$ such that $\theta_{i_1}^T k_i = 1$, and $\theta_{i_2}^T k_i = 0$, for all $j \neq i_1$. Thus, $\sum_{i=1}^{D} \theta_i^T k_i = 1$, whereas, $\sum_{i=1}^{D} \theta_i^T k_i > 1$. This is done for each $k$ such that $\sum_{i=1}^{D} \theta_i^T k_i > 1$. It can be verified that the cost $\sum_{t=0}^{T-1} \gamma_t^T r_t$ remains the same while using $\theta_{[0,T-1]}$ or $\theta_{[0,T-1]}$; whereas $\sum_{t=0}^{T-1} \theta_t^T \Lambda > \sum_{t=0}^{T-1} \theta_t^T \Lambda$. Thus the optimal solution of (14) must be the optimal solution of (15).

Relaxing the equality constraint of $b_{i,t}$ as $b_{i,t} \leq (\sum_{i=1}^{D} \theta_i^T k_i)$ results in the following MILP which is equivalent to (14):

$$\min_{\theta_{[0,T-1]}} \sum_{t=0}^{T-1} \left[ \gamma_t^T A + \gamma_t^T r_t \right] \quad (16)$$

subject to

$$\gamma(\gamma_t)_i = \sum_{j=1}^{D} b_j t_j, \quad b_{i,t} \leq \sum_{i=1}^{D} \theta_i^T k_i$$

$$\sum_{i=1}^{D} \theta_i^T k_i = 1, \quad \sum_{i=1}^{T} b_{i,t} = 1, \quad \sum_{i=t+2}^{D} b_{i,t} = 0$$

$$b_{i,t} \in \{0,1\}, \quad \theta_{i,t} \in \{0,1\}, \quad \forall t \in [0,T-1], i \in [1,D].$$

Problem (16) is a relaxed version of (15), therefore, any optimal solution of (16) is also an optimal solution of (15) if it is a feasible solution for (15). At this point, it is trivial to verify that the optimal solution of (16) is a feasible (and hence optimal) solution for (15), and hence optimal for (14).

C. Communication Cost as a Constraint

So far, we have considered the cost function of the form

$$J = \min_{u,\theta} E \left[ J_{LQG} + J_{Comm} \right],$$

where, $J_{Comm}$ is the communication cost. There are equivalent formulations of the this problem depending on the specific NCSS setup, e.g., constraint optimization problem:

$$\min_{u_{[0,T-1]}, \theta_{[0,T-1]}} E \left[ \sum_{t=0}^{T-1} x_t^T Q_1 x_t + u_t^T R u_t + x_t^T Q_2 x_t \mid \mathcal{I}_t \right],$$

subject to

$$E \left[ \sum_{t=0}^{T-1} \theta_t^T \Lambda \right] \leq b,$$

where $b \in \mathbb{R}^+$ is the budget; or, a bi-objective problem:

$$\min_{u_{[0,T-1]}, \theta_{[0,T-1]}} \left\{ f_1(u, \theta), f_2(u, \theta) \right\}, \quad (17)$$

with $f_1 = E \left[ \sum_{t=0}^{T-1} x_t^T Q_1 x_t + u_t^T R u_t + x_t^T Q_2 x_t \right]$, and $f_2 = E \left[ \sum_{t=0}^{T-1} \theta_t^T \Lambda \right]$. The solution of the bi-objective problem is characterized by Pareto frontier. Looking at Pareto curve for the section $f_2 \leq b$, one obtains the solution of the constrained budget problem. Moreover, solving the constrained budget problem for all $b \geq 0$, the Pareto frontier for the bi-objective problem is obtained.
Lemma 1: Consider the multi-objective problem
\[
\min_s \{ f_1(s), f_2(s), \ldots, f_m(s) \},
\]
and the equivalent weighted cost problem:
\[
\min_s \sum_{i=1}^m \alpha_i f_i(s), \quad \text{s.t.} \quad \sum_{i=1}^m \alpha_i = 1, \quad \alpha_i \geq 0,
\]
then \( s^* \) is a Pareto point for (18) if and only if \( s^* \) is the solution of (19) for some \( \{\alpha_i\} \).
The Pareto frontier for (17) can be constructed by optimizing the single objective function
\[
E \left[ \sum_{t=0}^{T-1} \alpha \left[ x_t^T Q_1 x_t + u_t^T R u_t + x_{T-1}^T Q_2 x_T \right] + (1-\alpha)T \lambda \right],
\]
for all \( \alpha \in [0, 1] \). Note that (20) is equivalent to (8) which can be solved following the discussion presented here.

IV. SIMULATION RESULTS

A. Example 1: Unstable Dynamics

Consider an NCS with unstable dynamics as:
\[
x_{t+1} = \begin{bmatrix} 1.01 & 0 \\ 0 & 1 \end{bmatrix} x_t + \begin{bmatrix} 0.1 & 0 \\ 0 & 0.15 \end{bmatrix} u_t + \sqrt{1.5} w_t
\]
where, \( w_t, x_0 \sim N(0, I_2) \). The horizon \( T \) is set to be 100. There are 5 links with delays ranging from 1 to 5 time-steps and the corresponding prices are [20, 13, 8, 2, 1]. The optimal utilization of the links is shown in Fig. 2. For this choice of the parameters the network mainly uses the fastest (link 1) and the slowest (link 5) links. Only for few instances, the system utilizes the link 4 and the rest of the links are not used. Thus, we note that the measurements sent by the Link 5 is never used in estimation except towards the end. Thus, the system can remain open-loop for most of the time.

To assure our simulation setup accuracy, we set \( \lambda_1 = 0 \) for all links, and we observe that only the fastest link is selected.

Similarly, setting \( \lambda_i \gg 1 \), the system selects the slowest link, as the communication cost is exorbitantly high compared to the LQG cost. Similar profile is observed for all \( \lambda \) when disturbance is removed, and system becomes deterministic, so the only observation required is the initial state, and no need to send any measurement at all. However, the constraint \( \sum_{i=1}^5 \theta_i \geq 1 \), forces the system to select the slowest link.

Let \( \rho_i(t) \) be defined as
\[
\rho_i(t) = \frac{\text{total utilization number of link } i}{t}.
\]
In Fig. 3A, we observe that mostly two of the links (fastest and slowest) are utilized, while the rest are hardly used. This behavior is linked with the structure of the MILP (16), and studying it is beyond the scope of this article. However, this raises an interesting question for multiple systems scenario: How could the links be distributed among sub-systems so that the link utilization is fair? Also, we observe that \( \rho_i(t) \) is very sensitive to the variations of \( \lambda_i \). The design of prices \( \Lambda \), as a time-varying or state-dependent variable, to achieve a desired utilization profile, is the subject of our future study.

In Fig. 3B we show the Pareto frontier of the bi-objective problem defined in (17). We notice that the minimum LQG cost (with fastest link being always selected) achievable for this set of parameters is 303.3 and the maximum LQG cost (with cheapest link being always selected) is 1503. The minimum communication cost is 100 (since cheapest link cost =1) which is associated with the maximum LQG cost.

B. Example 2: Stable dynamics

\[
\dot{x} = \begin{bmatrix} 0.5 & 0.05 \\ 0.5 & 0.9 \end{bmatrix} x + \begin{bmatrix} 0.1 & 0.01 \\ 0.05 & 0.15 \end{bmatrix} u + \sqrt{1.5} w_t
\]

In this setting, we similarly choose a network with 5 possible delay links (delays are 1,2,3,4,5 time steps.) with the costs: [10, 8, 2.5, 1.5, 1], such that lower delays are assigned with higher costs. The network utilization is shown in Figure 4 for this system, which follows the similar pattern as in the previous example.

V. CONCLUSION

In this article we address the problem of joint optimal LQG control and delay switching strategy in an NCS with a single stochastic LTI system. Assuming that the network utilization incurs cost, i.e. transmission with shorter delay is
more costly, we derive the optimal delay switching profile. The overall cost function consisting of the LQG cost plus communication cost, is shown to be decomposable in expectation assuming \textit{apriori} known prices. Having the separation property, the optimal laws can be computed offline as the solutions of an algebraic Riccati equation for the optimal control law, and a MILP, for the optimal switching profile.

VI. DISCUSSION

A. Stability Analysis

First, it is worth mentioning that in this work we study the finite horizon optimal design of control and transmission policies, and due to the linearity of the system dynamics, it is ensured that the state of the system remains bounded in expectation over any finite horizon time duration, if the cost of communication is finite. Therefore, talking about stability, which is an asymptotic system property, we look into the infinite time horizon. To do this, as we will discuss in the following (see Lemma 2), we consider the designed strategies in their limit \((k \to \infty)\) and show that under finite prices for communication, the system is asymptotically stable in mean-square sense.

We study stability of the described control system in infinite horizon under the steady-state optimal control and transmission policies, i.e. the limit of the strategies \((u^*_k, \theta^*_k)\), derived in the manuscript. It is straightforward to express the evolution of the system state \(x_k\), as follows:

\[
x_{k+1} = (A - BL_k) x_k + BL_k e_k + w_k,
\]

where, the estimation error \(e_k\) is defined in section III-A, and \(L_k = (R + B^T P_{k+1} B)^{-1} B^T P_{k+1} A\). Due to the existence of exogenous stochastic disturbance, we employ the concept of Lyapunov mean-square stability (LMSS), to investigate stability properties of the closed-loop system \((21)\). Let us first define the notion of LMSS, as follows.

\textbf{Definition 1 (\cite{21})}: An LTI system with state vector \(X_k\) is said to be Lyapunov mean-square stable (LMSS) if given \(\varepsilon > 0\), there exists \(\rho(\varepsilon)\) such that \(\|X_0\|_2 < \rho\) implies

\[
\sup_{k \geq 0} \mathbb{E} \left[\|X_k\|_2^2\right] \leq \varepsilon.
\]

From (9), one can see that the evolution of \(e_k\) is independent of the system state \(x_k\), and is only dependent on the noise realizations, the system matrix \(A\), and the transmission policy \(\theta_{k\text{-}D\text{-}k\text{-}1}\). Therefore, if it is shown that the optimal control gain \(L_k\) ensures asymptotic stability of the closed-loop system \(x_{k+1} = (A - BL_k) x_k\), where \(x_k\) is the state of the system \((21)\) in ideal case, i.e. assuming that no transmission delay exists, then LMSS is reduced to showing that the quadratic norm of the error state \(e_k\) is, in the limit, bounded in expectation. Before stating the main stability result, we revisit the following definition and Lemma:

\textbf{Definition 2 (\cite{22})}: A dynamical system \(x_{k+1} = f(x_k, k), x_0 = x(0)\), is said to be \textit{uniformly asymptotically stable in large} (UASL) with respect to \(x^*\) if the followings hold

i. given \(\varepsilon > 0\), there exists \(\delta > 0\) such that \(\|x^* - x_0\| \leq \delta\) implies \(\|x_k - x^*\| \leq \varepsilon\), for any \(k > 0\),

ii. given \(\delta > 0\), there exists \(\varepsilon > 0\) such that \(\|x^* - x_0\| \leq \delta\) implies \(\|x_k - x^*\| \leq \varepsilon\), for any \(k > 0\).

\textbf{Lemma 2 (\cite{22})}: Let \(P_k\) be the solution of the following discrete Riccati operator equation

\[
P_k = Q_1 + A^T (P_{k+1} - P_{k+1} B (R + B^T P_{k+1} B)^{-1} B^T P_{k+1}) A,
\]

where, \(Q_1 = Q_1^T \geq Q_1\). If \((A, B)\) is stabilizable, and \((A, Q_1)\) detectable, then \(P_k\) converges, in the operator norm, as \(k \to \infty\), to a positive operator \(P\) that is the unique positive solution to the associated algebraic Riccati equation

\[
P = Q_1 + A^T (P - PB (R + B^T P B)^{-1} B^T P A) A.
\]

In addition, the control and state generated by

\[
x_{k+1} = Ax_k + Bu_k, \quad x_0 = x(0),
\]

\[
u_k = - (R + B^T P B)^{-1} B^T P A x_k,
\]

is uniformly asymptotically stable in large (UASL) with respect to the origin \(x^* = 0\).

\textbf{Theorem 2}: Consider an LTI system described by the discrete time dynamics \((1)\) under the optimal state-feedback control \(u^*_k\), and the optimal transmission control \(\theta^*_k\) derived according to \((5)\). Under the controllability and stabilizability assumptions, and also assuming that the constraint \((2)\) holds at every time-step \(k \in \{1, 2, \ldots\}\), the closed-loop system \(x_{k+1} = (A - BL_k) x_k + BL_k e_k + w_k\) is Lyapunov mean-square stable.

\textbf{Proof}: Since the pairs \((A, B)\) and \((A, Q_1)\) are controllable and detectable, respectively, the closed-loop system \(x_{k+1} = (A - BL_k) x_k\) is ensured to be UASL, assuming that no transmission delay exists, i.e. \(e_k = 0\). This conclusion follows from Lemma 2. Therefore, the closed-loop matrix \((A - BL_k)\) is stable as \(k \to \infty\) and \(\lim_{k \to \infty} |x_k^*| \to 0\). Moreover, due to linearity of the system, it is ensured that there exists \(\varepsilon_c > 0\) such that \(\mathbb{E} \left[\|x_k^*\|_2\right] \leq \varepsilon_c\) at any time \(k\). Considering the transmission delays, the term \(e_k\) appears in the dynamics. However, as \(e_k\) is independent of \(x_k\), it is sufficient to show the quadratic norm of error state \(e_k\) is bounded in expectation for any \(k \leq 0\). Hence, according to the Definition 2 it must be ensured that, given \(0 < \varepsilon < \varepsilon_c\), there exists \(\bar{\rho}(\varepsilon)\) such that \(\|e_k\|_2 < \bar{\rho}\) implies

\[
\sup_{k \geq 0} \mathbb{E} \left[\|e_k\|_2^2\right] \leq \varepsilon.
\]

We consider the worst case evolution of error state over time, which happens when the transmission is always performed with the maximum delay, i.e. \(D\), and consequently, the system is not updated for maximum of \(D - 1\) time-steps. We then evaluate the dynamics of error over any interval of length \(D - 1\) over which no state information has been received. Assume that at a time-step \(k\) the controller has received one state information, and then the next update happens at...
time $k+D$. Therefore, over the interval $(k, k+D-1]$, the controller receives no state information. From (9), we know
\[
e_{k+D-1} = \sum_{j=1}^{D} A^{j-1} w_{k+D-1-j}.
\]

It then follows that
\[
E \left[ \|e_{k+D-1}\|_2^2 \right] = E \left[ \left\| \sum_{j=1}^{D} A^{j-1} w_{k+D-1-j} \right\|_2^2 \right]
\]
\[
= \sum_{j=1}^{D} E \left[ \|A^{j-1} w_{k+D-1-j}\|_2^2 \right] \leq \sum_{j=1}^{D} \|A^{j-1}\|_2^2 \text{tr}(W),
\]

where, the second equality follows due to statistical independence of the noise realizations, and the inequality follows from the multiplicativity property of matrix norms. Note that, as the time interval $(k, k+D-1]$ is generic, this is the possible maximum error norm the system is expected to have at any time-step, due to not having an update for the last $D-1$ time-steps. This ensures that the inequality is valid for any other transmission sequence $\delta_k$ for $k \in \{1, 2, \ldots\}$, optimal or non-optimal. Finally, boundedness of the error state $e_k$ and system state $x_k^e$ in expectation ensures that $x_k^e$ is also bounded in expectation at any time $k \in \{1, 2, \ldots\}$, which satisfies LMSS condition in Definition 1, and the proof is then complete.

\section{VII. APPENDIX}

A. Proof of Theorem 7

The LQG optimal value function at time $k+1$ is
\[
V^*_k = \min_{u_k} E \left[ \sum_{t=k+1}^{T-1} x_t^T Q_1 x_t + u_t^T R u_t + x_t^T Q_2 x_t | \tilde{I}_k \right].
\]

Knowing that $\tilde{I}_k \subset \tilde{I}_{k+1}$, the law of total expectation yields
\[
E[V^*_k | \tilde{I}_k] = \min_{u_{[k+1,T-1]}} E \left[ \sum_{t=k+1}^{T-1} x_t^T Q_1 x_t + u_t^T R u_t + x_t^T Q_2 x_t | \tilde{I}_k \right].
\]

Therefore, it is straightforward to re-write $V^*_k$ as follows:
\[
V^*_k = \min_{u_{[k+1,T-1]}} E \left[ x_{t-k+1}^T A x_{t-k+1} + u_t^T R u_t + V^*_k | \tilde{I}_k \right].
\]

Assume that $V^*_k$ can be expressed as follows:
\[
V^*_k = E[x_{t-k+1} | \tilde{I}_k]^T P_k E[x_{t-k+1} | \tilde{I}_k] + \pi_k \triangleq \tilde{x}_{t-k+1}^T P_k \tilde{x}_{t-k+1} + \pi_k,
\]

where, $\pi_k$ will be derived later as a term independent of the control $u_k$. Having (24) assumed, (23) can be re-written as
\[
V^*_k = \min_{u_k} E \left[ x_{t-k}^T Q_1 x_{t-k} + u_t^T R u_t + \tilde{x}_{t-k}^T P_{k+1} \tilde{x}_{t-k+1} + \pi_{k+1} | \tilde{I}_k \right].
\]

We define the apriori state estimate $\tilde{x}_k \triangleq E [x_k | \tilde{I}_{k-1}] = A \tilde{x}_{k-1} + B u_k$. Due to the fact that
\[
E[\tilde{x}_{t-k+1} | \tilde{I}_{t-k}] = E[\tilde{x}_{t-k+1} P_{k+1} \tilde{x}_{t-k+1} | \tilde{I}_{t-k}] = \tilde{x}_{t-k}^T P_{k+1} \tilde{x}_{t-k+1}
\]
then, (25) can be written as in the following:
\[
V^*_k = \min_{u_k} E \left[ x_{t-k}^T Q_1 x_{t-k} + u_t^T R u_t + \tilde{x}_{t-k}^T P_{k+1} \tilde{x}_{t-k+1} + \pi_{k+1} | \tilde{I}_k \right].
\]

Plugging the optimal control $u^*_k$ in (26), together with replacing $x_k$ with its equivalent expression $e_k + \tilde{x}_k$, result in
\[
V^*_k = E[e_{t-k}^T \left( B^T \hat{R} B + \hat{A}^T P_{k+1} \hat{A} + Q_1 \right) e_k | \tilde{I}_k] \quad (27)
\]
\[
+ E[e_{t-k}^T Q_1 e_k + \xi_{k+1} P_{k+1} \xi_{k+1} + \pi_{k+1} | \tilde{I}_k],
\]

where, $\tilde{B}_k = (R + B^T P_{k+1} B)^{-1} B^T P_{k+1} A$, and $\tilde{A}_k = A - B \tilde{B}_k$. The equality (27) is ensured since
\[
E[e_{t-k}^T Q_1 e_k | \tilde{I}_k] = E[e_{t-k}^T Q_1 x_k | \tilde{I}_k] - E[(E[x_k | \tilde{I}_k]^T Q_1 E[x_k | \tilde{I}_k]) | \tilde{I}_k] = 0.
\]

Comparing (27) with (24), the followings are concluded
\[
\pi_k = E \left[ e_{t-k}^T Q_1 e_k + \xi_{k+1}^T P_{k+1} \xi_{k+1} + \pi_{k+1} | \tilde{I}_k \right] = E \left[ \sum_{t=k+1}^{T} e_{t-k}^T Q_1 e_t + e_{t-k}^T Q_2 e_t + \sum_{t=k+1}^{T} \xi_{t}^T P_{t} \xi_{t} | \tilde{I}_k \right].
\]

From definitions of $\xi_k$ and $e_k$, it concludes for all $k \geq 1$ that
\[
\xi_k + e_k = x_k - \tilde{x}_k = A e_{k-1} + w_{k-1}.
\]

Knowing that $E[e_{t-k}^T P_{k+1} \tilde{x}_{t-k} | \tilde{I}_k] = \xi_{t-k} P_{k+1} E[e_k | \tilde{I}_k] = 0$, we obtain
\[
E[e_{t-k}^T P_k \xi_k | \tilde{I}_k] + E[e_{t-k}^T P_k e_k | \tilde{I}_k] = E[(\xi_k + e_k)^T P_k (\xi_k + e_k) | \tilde{I}_k] = E[(A e_{k-1} + w_{k-1})^T P_k (A e_{k-1} + w_{k-1}) | \tilde{I}_k] = E[e_{t-k}^T A^T P_k A e_{k-1} | \tilde{I}_k] + tr(P_k W).
\]

Then it follows that
\[
E \left[ \sum_{t=k+1}^{T} \xi_{t}^T P_{t} \xi_{t} | \tilde{I}_k \right] = \sum_{t=k+1}^{T} tr(P_t W)
\]
\[
- E \left[ \sum_{t=k+1}^{T} e_{t-k}^T P_{t} e_{t-k} | \tilde{I}_k \right] + E \left[ \sum_{t=k+1}^{T} e_{t-k}^T A^T P_{t} A e_{t-k} | \tilde{I}_k \right]
\]

Finally, defining $\hat{P}_t = Q_1 + A^T P_{t+1} A - P_t$, for all $T > t \geq k$, the expression (28) for $\pi_k$ can be re-written as
\[
\pi_k = E \left[ \sum_{t=k}^{T-1} e_{t-k}^T (Q_1 + A^T P_{t+1} A) e_t + e_{t-k}^T Q_2 e_t | \tilde{I}_k \right]
\]
\[
- E \left[ \sum_{t=k}^{T-1} e_{t-k}^T P_{t} e_{t-k} | \tilde{I}_k \right] + \sum_{t=k+1}^{T} tr(P_t W)
\]
\[
= E \left[ e_{t-k}^T P_k e_{t-k} + \sum_{t=k}^{T-1} e_{t-k}^T P_{t} e_{t-k} | \tilde{I}_k \right] + \sum_{t=k+1}^{T} tr(P_t W).
\]
B. Proof of Proposition 2

Consider two cases; $k \geq D$, and $k < D$. At any time $k \geq D$, the latest information the controller can have is $x_{k-1}$, only if $\theta_{k-1}^i = 1$. If $\theta_{k-1}^i = 0$, the latest information available is $x_{k-2}$, only if $\theta_{k-2}^i \lor \theta_{k-2}^j = 1$ (‘\lor’ is the logical OR operator). The algebraic representation of the logical constraint $\theta_{k-2}^i \lor \theta_{k-2}^j = 1$ is $\theta_{k-2}^i + \theta_{k-2}^j - \theta_{k-2}^i \theta_{k-2}^j = 1$. Similarly, we reach

$$E[x_k|\mathcal{I}_k] = \theta_{k-1}^i E[x_k|x_{k-1}, U_{k-1}] +$$

$$(1 - \theta_{k-1}^i) \left( \theta_{k-2}^1 \lor \theta_{k-2}^2 \right) E[x_k|x_{k-2}, U_{k-1}] +$$

$$(1 - \theta_{k-1}^i) (1 - \theta_{k-2}^1) \left( \theta_{k-3}^1 \lor \theta_{k-3}^2 \right) E[x_k|x_{k-3}, U_{k-1}] +$$

$$\ldots +$$

$$\prod_{d=1}^{D-1} \prod_{j=1}^{d} \left( 1 - \theta_{k-d}^i \right) \left( \lor_{i=1}^{k} \theta_{k-d}^i \right) E[x_k|x_{k-D}, U_{k-1}]$$

For $k < D$, the oldest information the controller can have is $x_0$, only if $\lor_{j=1}^{k} \theta_{0}^j = 1$. Otherwise, if at time 0, the used link(s) had delay(s) greater than $k$, then $x_0$ is not available at time $k$, hence statistics of $x_0$ are used. Thus for $k < D$,

$$E[x_k|\mathcal{I}_k] = \theta_{k-1}^i E[x_k|x_{k-1}, U_{k-1}] +$$

$$(1 - \theta_{k-1}^i) \left( \theta_{k-2}^1 \lor \theta_{k-2}^2 \right) E[x_k|x_{k-2}, U_{k-1}] +$$

$$\ldots +$$

$$\prod_{d=1}^{k-1} \prod_{j=1}^{d} \left( 1 - \theta_{k-d}^i \right) \left( \lor_{i=1}^{k} \theta_{k-d}^i \right) E[x_k|x_{0}, U_{k-1}] +$$

$$\prod_{d=1}^{k} \prod_{j=1}^{d} \left( 1 - \theta_{k-d}^i \right) E[x_k|\mathcal{I}_0, U_{k-1}]$$

For $k < D$, the same definition of $b_{1,k}, b_{2,k}, \ldots, b_{k,k}$ under-braced in (29) is used, while we define $b_{k+1,k} = \prod_{d=1}^{k} \prod_{j=1}^{d} (1 - \theta_{k-d}^i)$ and $b_{k+2,k} = b_{k+3,k} = \ldots = b_{D,k} = 0$. Finally, employing $E[x_k|x_{-1}, U_{k-1}] = E[x_k|\mathcal{I}_0, U_{k-1}]$, the proof then readily follows.

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