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A Timer-Based Distributed Channel Access Mechanism in Networked Control Systems

Tahmoores Farjam, Themistoklis Charalambous, and Henk Wymeersch

***Abstract*—We consider a system consisting of multiple heterogeneous control subsystems sharing a common communication resource for accomplishing their control tasks. Despite the numerous advantages that such networked control systems (NCSs) offer, their implementation is limited in practice due to the limited communication resources. We propose a novel distributed approach for the resource allocation problem in NCSs by which the subsystems can coordinate to access the network. More specifically, we develop a deterministic distributed scheme with which the subsystem with the highest cost is selected, based only on local information without requiring explicit communication between the subsystems. The efficiency of our scheme is demonstrated via simulations and it is compared with a centralized approach and other relevant approaches.**

***Index Terms*—Networked control systems, distributed channel access, cost of information loss, timers.**

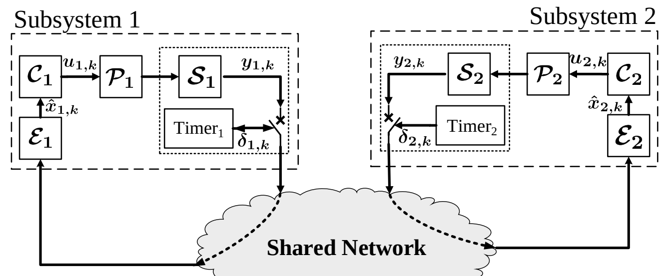

Fig. 1. Example of the NCS layout where two subsystems compete to transmit their local measurements through the limited capacity shared network. $\mathcal{P}_i$ represents the plant of subsystem $i \in \{1, 2\}$, $\mathcal{S}_i$ its sensor, $\mathcal{E}_i$ its estimator, and $\mathcal{C}_i$ its controller. Note that the timer is embedded in the sensor.

I. INTRODUCTION

The use of a shared network to connect spatially distributed (possibly heterogeneous) systems provides flexible architectures with reduced installation and maintenance costs to existing applications, and at the same time encourages the industrial world to explore the potential for burgeoning breakthrough applications; see, e.g., [1], [2]. Research in NCSs dates back to the 1970s (a thorough literature review can be found in [3]–[5]) and such systems have been implemented in several domains, such as power plants and manufacturing industry, where information is collected from different locations and then communicated to a central station. Then, important decisions are made centrally and communicated to different locations. However, the use of a shared network and distributed decision making introduce new challenges, since traditional approaches and designs no longer work, due to the unprecedented tight coupling between control and communication.

The problem of how subsystems access the shared network constitutes one of the biggest challenges in NCSs. This challenge was mainly targeted by centralized scheduling policies; see, e.g., [6]–[13] and references therein. However, the central nature of the implementation of these systems has been limiting. To allow for a distributed allocation of the resources, random access protocols have been proposed; see, e.g., [14], [15]. Despite the relative simplicity and practicality of these approaches, their outcome is not necessarily preferable, because the performance degrades with the number of users due to the random nature of accessing the channel. More recently, distributed approaches have been proposed, adopting contention-based medium access control (MAC) in which nodes compete for accessing the channel; see, e.g., [16], [17]. In [16] a combined deterministic and probabilistic MAC process is proposed in which the channel access is prioritized according to a time error-dependent measure. In [17] a deterministic MAC mechanism is proposed in which priority is state-dependent and it is implemented via a binary countdown technique. While the approach in [17] improves scalability and dynamically prioritizes channel access among multiple subsystems, its binary countdown technique results in collisions when subsystems have similar priorities, especially when the number of bits for contention resolution available do not scale with the number of subsystems.

In this paper, inspired by [17], we propose a distributed channel access mechanism for NCSs, herein called TBCoIL, in which each subsystem employs a timer for accessing the channel. The timer for each subsystem is associated with the cost imposed by that subsystem to the whole system. A variation of this mechanism in which the timer is a function of the channel quality only is a well-celebrated result in wireless cooperative networks [18]. Unlike [17], the timer is in continuous space, thus reducing collision probabilities and the requirement for synchronization between the subsystems within the contention period.

The remainder of the paper is organized as follows. In Section II, we provide the system model and preliminaries necessary for the development of our results. In Section III, we describe the proposed distributed channel access mechanism, and in Section IV we demonstrate its performance. In Section V, we draw conclusions and discuss future directions.

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II. System Model and Preliminaries

We consider NCSs consisting of N dynamical subsystems, each including a local state estimator and feedback controller. The dynamics of each subsystem can be modeled by a linear time-invariant stochastic process with the following discrete-time state-space representation:

$$x_{i,k+1} = A_i x_{i,k} + B_i u_{i,k} + w_{i,k}, \quad (1a)$$

$$y_{i,k} = C_i x_{i,k} + \nu_{i,k}, \quad (1b)$$

where $x_{i,k} \in \mathbb{R}^{n_i}$, $y_{i,k} \in \mathbb{R}^{p_i}$ and $u_{i,k} \in \mathbb{R}^{m_i}$ are the local states, outputs and controller inputs at time step k, respectively. Moreover, $A_i \in \mathbb{R}^{n_i \times n_i}$, $C_i \in \mathbb{R}^{p_i \times n_i}$ and $B_i \in \mathbb{R}^{n_i \times m_i}$ are the system matrices for each subsystem $i \in \{1, 2, \ldots, N\}$. The stochastic disturbances and measurement noises are denoted by $w_{i,k}$ and $\nu_{i,k}$. They are assumed to be Gaussian with independently and identically distributed (i.i.d.) entries with zero mean and covariances $W_{i,k}$ and $V_{i,k}$, respectively.

The local measurements, $y_{i,k}$ are transmitted through a limited capacity network to be received by their corresponding state estimator; see Fig 1. However, due to the limitations of the communication resources, only a limited number of subsystems can transmit their data at k. The variable $\delta_{i,k} \in \{0, 1\}$ is defined such that it represents whether subsystem i transmits at k or not as follows

$$\delta_{i,k} = \begin{cases} 1, & y_{i,k} \text{ is transmitted,} \\ 0, & \text{otherwise.} \end{cases}$$

We consider the case of reliable channels, and therefore if $\delta_{i,k} = 1$ and no collision happens, the data packet is guaranteed to be received at its destination.

Each subsystem i includes a local controller which computes the state feedback control commands $u_{i,k}$ by

$$u_{i,k} = L_i \hat{x}_{i,k|k}, \quad (2)$$

where L_i is a stabilizing feedback matrix of proper dimensions and $\hat{x}_{i,k|k}$ represents the *a posteriori* state estimate of subsystem i. Here, we aim at minimizing the following quadratic cost function over the infinite horizon

$$J_{i,0} = \mathbb{E}\left\{ \sum_{k=0}^{\infty} \left(x_{i,k}^T Q_i x_{i,k} + u_{i,k}^T R_i u_{i,k} \right) \right\}, \quad (3)$$

where Q_i and R_i are constant positive definite matrices of appropriate dimensions. The stabilizing feedback matrix L_i to be substituted in eq. (2) for determining the optimal control commands for minimizing J is given by [19]

$$L_i = -(B_i^T \Pi_i B_i + R_i)^{-1} B_i^T \Pi_i A_i, \quad (4)$$

where the symmetric positive semidefinite matrix Π_i is the solution of the following discrete-time Riccati equation

$$\Pi_i = A_i^T \Pi_i A_i - A_i^T \Pi_i B_i (B_i^T \Pi_i B_i + R_i)^{-1} B_i^T \Pi_i A_i + Q_i.$$

The local estimator keeps track of the set of observations and the parameter $\delta_{i,k}$ up to time k, and provides the state estimates required by the controller in eq. (2). Since the disturbances and noises are assumed to be Gaussian, Kalman filter gives the minimum mean square estimate. Hence, using it as the local estimator, the *a priori* and *a posteriori* state estimates, denoted by $\hat{x}_{i,k+1|k}$ and $\hat{x}_{i,k+1|k+1}$, respectively, can be derived by the following set of equations [20]

$$\hat{x}_{i,k+1|k} = A_i \hat{x}_{i,k|k} + B_i u_{i,k}, \quad (5a)$$

$$P_{i,k+1|k} = (A_i + B_i L_i) P_{i,k|k} (A_i + B_i L_i)^T + W_i, \quad (5b)$$

$$K_{i,k+1} = P_{i,k+1|k} C_i^T \left(C_i P_{i,k+1|k} C_i^T + V_i \right)^{-1}, \quad (5c)$$

$$\hat{x}_{i,k+1|k+1} = \hat{x}_{i,k+1|k} + \delta_{i,k+1} K_{i,k+1} (y_{i,k+1} - C_i \hat{x}_{i,k+1|k}), \quad (5d)$$

$$P_{i,k+1|k+1} = (I - \delta_{i,k+1} K_{i,k+1} C_i) P_{i,k+1|k}. \quad (5e)$$

III. Distributed Channel Access Mechanism

In this work, we investigate the case where a time-slotted medium access communication protocol is implemented. The communication channel is assumed to be constrained by

$$\sum_{i=1}^{N} \delta_{i,k} \leq 1, \quad (6)$$

meaning that only one subsystem can transmit successfully in a specific time slot. In case two or more subsystems transmit simultaneously, there is a collision and the packets are dropped.

The proposed method is based on the idea that each subsystem possesses a timer which is used as a way of resolving the contention for channel access in a distributed manner. The basic idea is that at the beginning of a time slot in which all subsystems are synchronized, the timer for each subsystem commences. The value of each of these local timers, denoted by $t_{i,k}$, is inversely proportional to a local cost $m_{i,k}$, i.e.,

$$t_{i,k} = \frac{\lambda}{m_{i,k}}, \quad (7)$$

where λ is a constant. Hence, the timer of the subsystem with the largest cost $m_{i,k}$ expires first. The subsystem, whose timer reaches zero first, transmits a short duration flag packet immediately, thus informing all other subsystems in the network to stop their timers and back off. Therefore, this subsystem can start transmitting its local measurements after the flag packet. Since the size of this packet is very small, for simplicity in this work, we assume its duration is negligible and thus subsystems transmit without any collision. For this reason, in this work we avoid any quantitative comparison with relevant schemes, such as that in [17]. As the duration of the time slot ends, the subsystems are re-synchronized and their timers are updated to their new values according to $m_{i,k}$ and the procedure is repeated.

It can be ensured that the contention period is considerably less than the duration of the time slot by fine-tuning λ. This parameter is a constant which can be determined according to the application and imposed network constraints. Its value can be neither too large, since it results in increased contention period and consequently higher latency, nor too small, since the scale of the network and its capacity impose a lower bound on λ and thus it cannot be set to any value. Furthermore, the units of λ depend on the units of $m_{i,k}$ and are chosen such that the result of eq. (7) is in the desired units of time.

Using this distributed channel access mechanism, herein called TBCoIL, the communication resources can be allocated in a distributed fashion based merely on local information. As a result, no explicit communication between subsystems is required and the overall overhead can be reduced significantly. The procedure described is depicted in Fig. 2 for an example of two subsystems competing for the channel in two successive time slots.

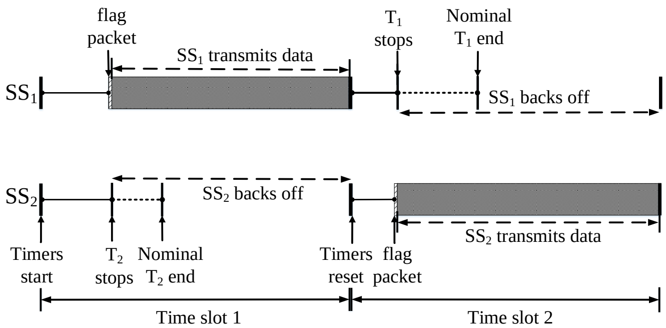

Fig. 2. Example of two subsystems competing for the channel in two successive time slots. Subsystem 1 (denoted as SS_1) has the largest induced error in the first time slot and gets the access to the channel. Subsequently, subsystem 2 (denoted as SS_2), that did not communicate in the first time slot, in the second time slot gets to have a larger induced error. Here, $m_{2,2} > m_{1,2}$, where m represents the local cost, and thus SS_2 gets access to the channel.

A. Timer setup

The implementation of TBCoIL requires quantification of the parameter $m_{i,k}$. Herein, for the purpose of exposition we assume that $m_{i,k}$ represents the Cost of Information Loss (CoIL) introduced in [10], i.e., $m_{i,k} = \mathrm{CoIL}_{i,k}$. As the naming suggests, $\mathrm{CoIL}_{i,k}$ is the cost imposed by subsystem i in case it does not transmit its measurements at k. In principle, it could be associated with any error that we choose as a measure for prioritizing transmission. CoIL for subsystem i at time step k is defined as

$$\mathrm{CoIL}_{i,k} = \mathrm{tr}\left(\Gamma_i(P_{i,k|k-1} - P_{i,k|k})\right), \tag{8}$$

where $\Gamma_i = L_i^T(B_i^T\Pi_i B_i + R_i)L_i$ and the the feedback matrix, denoted by L_i, is given by (4). Furthermore, $P_{i,k|k-1}$ and $P_{i,k|k}$ are the *a priori* and *a posteriori* error covariance matrices as defined in (5b) and (5e), respectively.

It is shown in [10] that minimizing the sum of CoIL for all subsystems is equivalent to minimizing (3). A significant advantage of choosing $\mathrm{CoIL}_{i,k}$ is that it can be computed at the sensor side directly, since it only requires initial conditions on the error covariance matrix and noise statistics (cf. (5b) and (5e)) at the beginning and, hence, no communication with the estimator is required; see Fig. 1.

Since λ in (7) is the same for all subsystems, a larger CoIL corresponds to a smaller value set for the corresponding timer. Consequently, since time is segmented into slots of a fixed duration and the subsystems are synchronized, the timer of the subsystem with the largest CoIL reaches zero first. As a result, the subsystem with the highest CoIL transmits to minimize the overall cost.

Remark 1: In [18] the concept of timers is used in the context of relay selection and the timer depends only on the channel quality, but in our case the timer depends on the evolution of local errors that evolve with the lack of communication, and this interplay is what impacts the performance of networked control systems the most.

Remark 2: This idea can be extended to the case where more than one subsystems can transmit successfully in a specific time slot, i.e., $\sum_{i=1}^{N}\delta_{i,k} \leq r$, where r is a natural number greater than 1. In such a case, subsystems with non zero timers back off only after they have heard r flag signals. Additionally, nodes that already transmitted a flag signal wait for all r flag signals to be transmitted before they start the data transmission. Note that the size of the data packet depends on the subsystem sending the r-th flag signal. In the case there exist r individual channels, if subsystems have the capability, they may have timers for r distinct channels.

IV. Numerical Results

For the examples to follow, we assume that the NCS consists of subsystems belonging to two homogeneous classes of dynamical subsystems. The first class, denoted by I, consists of identical unstable subsystems, while the remaining stable subsystems form the second class, denoted by II. Apart from the system matrix (A), the properties of both types of subsystems are described by the same matrices. The subsystem are defined by

$$A_I = \begin{bmatrix}1.1 & 0.1\\ 0 & 1\end{bmatrix} A_{II} = \begin{bmatrix}0.9 & 0\\ 0 & 0.9\end{bmatrix}, B = C = I_{2\times 2}.$$

Moreover, state estimates and feedback control law are determined as discussed, assuming that the covariance matrices of the stochastic disturbances and measurement noises are

$$W_i = \begin{bmatrix}0.03 & 0\\ 0 & 0.01\end{bmatrix}, V_i = \begin{bmatrix}0.01 & 0\\ 0 & 0.05\end{bmatrix}.$$

The timers are set using the CoIL corresponding to the introduced quadratic cost function given in eq. (3) with $Q = I_{2\times 2}$ and $R = 0.01 I_{2\times 2}$.

Example 1: First, we demonstrate how our proposed timer-based distributed channel access mechanism (TBCoIL) operates for a simple case of 3 subsystems, where only subsystem 1 is stable, in 15 time steps. First, a randomly generated value for $P_{0|0}$ is assigned to each subsystem. Thereafter, all computations are done locally using the recursive equations given in eq. (5). As shown in Fig. 3, at every time step, the subsystem with the highest CoIL has the smallest timer and therefore transmits its measurements. At the next step, CoIL for this subsystem drops, since its estimations are based on more recent data while this cost has increased for the remaining contenders. Here, for illustrative purposes, λ is set to 3.34×10^{-3} $m^2 s$ (meters squared times seconds), and the best timers reach zero between 50 to 77 milliseconds. This value can be chosen arbitrarily and fine-tuned to satisfy the constraints imposed by any specific application.

The resources are allocated in a way that only subsystems 2 and 3 transmit which is expected due to their unstable nature. A more precise estimate of the states of subsystems that belong to class I would reduce the defined cost more considerably than the stable one. Hence, the contention for the communication

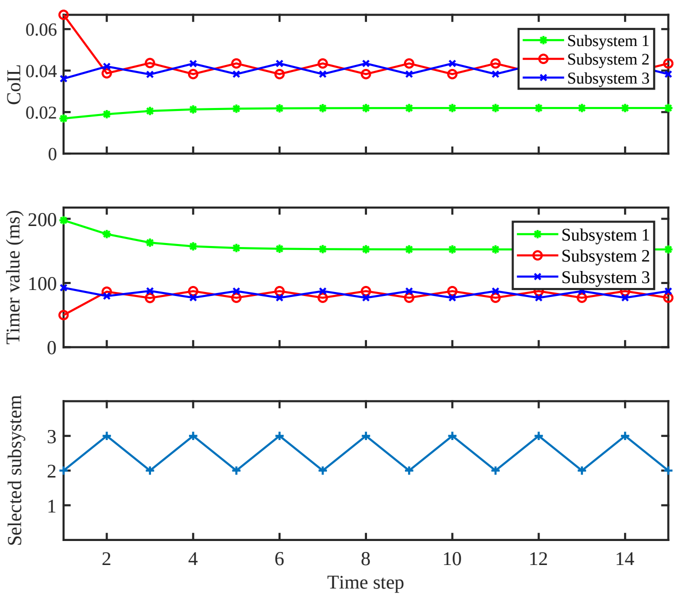

Fig. 3. Resource allocation with TBCoIL for a simple case of two unstable subsystems and a stable one sharing a single channel. Since the CoIL for unstable subsystems is always higher, their timers expire faster and the channel is dedicated to them.

resources is confined between the unstable subsystems. At each step, the uncertainty associated with the estimation for the transmitting subsystem is reduced, while it possibly (in case it did not converge) grows for the rest. Hence, its CoIL becomes less than the other unstable subsystem and cannot claim the next time slot. This procedure is repeated and consequently each transmits every other step.

Example 2: Next, we compare the performance of TBCoIL with other relevant methods in large scale networks. Here, we also consider the centralized version of TBCoIL where a central scheduler uses the same concept to allocate the channel to the subsystem with the highest CoIL. This method gives the lower bound on the achievable total cost. In addition, a method based on utilizing the concept of *Value of Information* (VoI) in the timers setup, herein called *Timer-Based Value of Information* (TBVoI), is studied. Using this concept, the local cost in eq. (7) is set to [7, Eq. (11)]

$$\begin{aligned} m_{i,k} =& \mathbb{E}\left\{(x_{i,k}-\hat{x}_{i,k|k-1})^T\Gamma_{i,k}(x_{i,k}-\hat{x}_{i,k|k-1})\right\} \\ &-\mathbb{E}\left\{(x_{i,k}-\hat{x}_{i,k|k})^T\Gamma_{i,k}(x_{i,k}-\hat{x}_{i,k|k})\right\} \\ =& \operatorname{tr}(\Gamma_{i,k}\tilde{P}_{i,k}), \end{aligned}$$

where $\tilde{P}_{i,k} = \tilde{e}_{i,k}\tilde{e}_{i,k}^T$ and $\tilde{e}_{i,k} = K_{i,k}(y_{i,k} - C_i\hat{x}_{i,k|k-1})$. Finally, the *round-robin* scheme is used to benchmark the performance in terms of reduction of the defined quadratic cost. This method requires no communication between nodes (once the scheduling has been agreed) and each subsystem transmits without collision according to the agreed sequence.

The results of simulation are averaged over 50 runs for NCSs consisting of 6 up to 42 subsystems, where only half of them can transmit successfully at each time step. Furthermore, only half of the participants are stable, while the rest belong to class I. As the results Fig. 4 indicate, round-robin has the worst performance. This outcome is expected since in this scheme the subsystems transmit according to a sequence which is randomly chosen when initiating. This results in equal resource distribution regardless of the properties of the involved systems or their initial conditions. As aforementioned in the discussion for the results shown in Fig. 3, selected subsystems for minimization of CoIL would not distribute the resources equally.

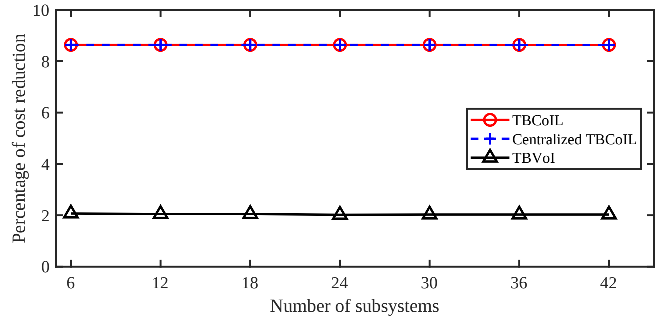

Fig. 4. Percentage of reduction of cost achievable through TBCoIL, its centralized version and TBVoI compared to round-robin in NCSs with different number of subsystems.

The centralized version of TBCoIL gives the least possible cost and leads to 8.64% improvement, whereas TBVoI reduces the cost only by 2.1%. The variation of the improvements is negligible, since it is assumed that the available resources are proportional to the number of involved subsystems and thus the cost grows linearly. It should be noted that the optimal results are also achieved with TBCoIL in a decentralized manner. This outcome is expected since the negligible duration of the flag packets guarantees successful transmission. Therefore, the optimal performance is achieved without requiring any explicit communication among subsystems. Hence, using this method, the overall overhead is substantially reduced without any negative impact on the performance. Moreover, in terms of computational costs, the computational complexity of the decentralized implementation is independent of the number of involved subsystems thus ensuring scalability.

Example 3: We consider a case similar to Example 2, in which class I consists of more unstable subsystems defined by

$$A_I = \begin{bmatrix} 1.4 & 0 \\ 0 & 1.2 \end{bmatrix}.$$

The results depicted in Fig. 5 show that TBCoIL reduces the cost more significantly in this case (18.78%). Due to the increased instability and the larger control action, deviation of state estimates from real values result in a faster growth of accumulated error. Consequently, a higher cost is imposed if the stable subsystems transmit instead of the unstable ones. Additionally, we observe that although the performance of TBVoI is suboptimal, TBCoIL and its centralized version outperform it by only 0.1%. The reduced difference in the performance of timer-based approaches is due the more unstable nature of subsystems. As a result, the change in covariance matrix and deviation of estimations from measurements are in almost the same order for subsystems of class I, hence making both approaches result in a similar channel access sequence.

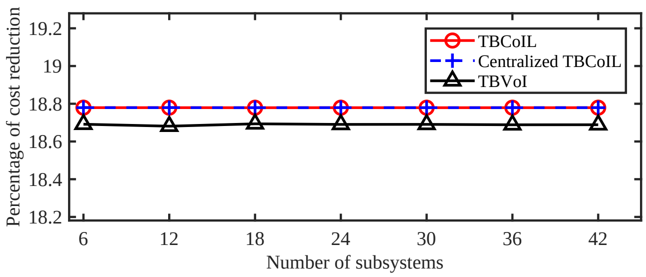

Fig. 5. Performance of different methods compared to round-robin in terms of cost reduction. Although the performance of TBVoI is suboptimal, TBCoIL and its centralized version outperform it by only 0.1%.

V. Conclusions and Future Directions

A. Conclusions

In this paper, we proposed a novel distributed method for the resource allocation problem in NCSs consisting of subsystems which are capable of local computations. For enabling a distributed approach to this problem, we introduced the concept of local timers as a measure to prioritize the communication of subsystems that reduce the overall cost of the system. We used CoIL as the relevant cost metric to demonstrate the functionality of the timers in the proposed mechanism, which enables the subsystem with the smallest timer value to transmit its data without collision based solely on the available local information. Simulation results show that the proposed method improves the performance in comparison with TBVoI and round-robin scheme. Moreover, this approach performs identically to the case of the centralized optimal scheduler in which no collisions occur, but it is completely distributed with no communication overhead.

B. Future directions

Part of ongoing research is to investigate the case for which there are collisions in the flag signals as well, not allowing the systems which are transmitting to know that other nodes have been transmitting at the same time resulting in collision during data transmissions.

Cases for which channel access depends on the state of the subsystems have been considered [21]–[23]. Future work will consider wireless communications allowing for imperfect channels, and with our setup, the concept of the timer can be extended to account for both the state of the subsystems as well as the channel quality.

Furthermore, energy efficient distributed MAC mechanisms with transmission power constraints using our setup, such as in [24]–[26], will be considered.

References

[1] M. Sha, D. Gunatilaka, C. Wu, and C. Lu, "Empirical Study and Enhancements of Industrial Wireless Sensor-Actuator Network Protocols," *IEEE Internet of Things Journal*, vol. 4, no. 3, pp. 696–704, June 2017.

[2] A. Aijaz, M. Dohler, A. H. Aghvami, V. Friderikos, and M. Frodigh, "Realizing the Tactile Internet: Haptic Communications over Next Generation 5G Cellular Networks," *IEEE Wireless Communications*, vol. 24, no. 2, pp. 82–89, April 2017.

[3] L. Schenato, B. Sinopoli, M. Franceschetti, K. Poolla, and S. S. Sastry, "Foundations of Control and Estimation Over Lossy Networks," *Proceedings of the IEEE*, vol. 95, no. 1, pp. 163–187, Jan. 2007.

[4] J. P. Hespanha, P. Naghshtabrizi, and Y. Xu, "A survey of recent results in networked control systems," *IEEE Special Issue on Technology of Networked Control Systems*, vol. 95, no. 1, pp. 138–162, Jan. 2007.

[5] R. A. Gupta and M. Y. Chow, "Networked Control System: Overview and Research Trends," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 7, pp. 2527–2535, July 2010.

[6] L. Zhao, W. Zhang, J. Hu, A. Abate, and C. J. Tomlin, "On the Optimal Solutions of the Infinite-Horizon Linear Sensor Scheduling Problem," *IEEE Transactions on Automatic Control*, vol. 59, no. 10, pp. 2825–2830, Oct. 2014.

[7] A. Molin, C. Ramesh, H. Esen, and K. H. Johansson, "Innovations-based priority assignment for control over CAN-like networks," in *IEEE Conference on Decision and Control (CDC)*, Dec 2015, pp. 4163–4169.

[8] M. H. Mamduhi, A. Molin, D. Tolic, and S. Hirche, "Error-dependent data scheduling in resource-aware multi-loop networked control systems," *Automatica*, vol. 81, pp. 209–216, 2017.

[9] D. Han, J. Wu, H. Zhang, and L. Shi, "Optimal sensor scheduling for multiple linear dynamical systems," *Automatica*, vol. 75, no. Supplement C, pp. 260–270, 2017.

[10] T. Charalambous, A. Ozcelikkale, M. Zanon, P. Falcone, and H. Wymeersch, "On the resource allocation problem in wireless networked control systems," in *IEEE Conference on Decision and Control (CDC)*, 2017, pp. 4147–4154.

[11] H. Zhang, R. Ayoub, and S. Sundaram, "Sensor selection for Kalman filtering of linear dynamical systems: Complexity, limitations and greedy algorithms," *Automatica*, vol. 78, pp. 202–210, 2017.

[12] S. Wu, X. Ren, S. Dey, and L. Shi, "Optimal Scheduling of Multiple Sensors with Packet Length Constraint," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 14 430–14 435, 2017.

[13] M. Zanon, T. Charalambous, H. Wymeersch, and P. Falcone, "Optimal Scheduling of Downlink Communication for a Multi-Agent System With a Central Observation Post," *IEEE Control Systems Letters*, vol. 2, no. 1, pp. 37–42, Jan 2018.

[14] M. Tabbara and D. Nesic, "Input-Output Stability of Networked Control Systems With Stochastic Protocols and Channels," *IEEE Transactions on Automatic Control*, vol. 53, no. 5, pp. 1160–1175, June 2008.

[15] M. Donkers, W. Heemels, D. Bernardini, A. Bemporad, and V. Shneer, "Stability analysis of stochastic networked control systems," *Automatica*, vol. 48, no. 5, pp. 917–925, 2012.

[16] M. H. Mamduhi, M. Kneissl, and S. Hirche, "Decentralized event-triggered medium access control for networked control systems," in *IEEE Conference on Decision and Control (CDC)*, Dec 2016, pp. 513–519.

[17] M. H. Mamduhi, M. Vilgelm, W. Kellerer, and S. Hirche, "Prioritized contention resolution for random access networked control systems," in *56th IEEE Conference on Decision and Control (CDC)*, 2017, pp. 6689–6695.

[18] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 3, pp. 659–672, March 2006.

[19] K. J. Åström, *Introduction to stochastic control theory*, ser. Mathematics in science and engineering. New York, London: Academic press, 1970, vol. 70.

[20] B. Sinopoli, L. Schenato, M. Franceschetti, K. Poolla, M. I. Jordan, and S. S. Sastry, "Kalman filtering with intermittent observations," *IEEE Transactions on Automatic Control*, vol. 49, no. 9, pp. 1453–1464, Sept 2004.

[21] C. Ramesh, *State-based Channel Access for a Network of Control Systems*. KTH Royal Institute of Technology, 2014.

[22] A. Molin and S. Hirche, "A bi-level approach for the design of event-triggered control systems over a shared network," *Discrete Event Dynamic Systems*, vol. 24, no. 2, pp. 153–171, 2014.

[23] M. H. Mamduhi, D. Tolić, and S. Hirche, "Decentralized event-based scheduling for shared-resource Networked Control Systems," in *European Control Conference (ECC)*, July 2015, pp. 947–953.

[24] W. Yang, C. Yang, H. Shi, L. Shi, and G. Chen, "Stochastic link activation for distributed filtering under sensor power constraint," *Automatica*, vol. 75, pp. 109–118, 2017.

[25] T. Iwaki, Y. Wu, J. Wu, H. Sandberg, and K. H. Johansson, "Wireless Sensor Network Scheduling for Remote Estimation under Energy Constraints," in *IEEE Conference on Decision and Control (CDC)*, 2017, pp. 3362–3367.

[26] X. Ren, J. Wu, K. H. Johansson, G. Shi, and L. Shi, "Infinite Horizon Optimal Transmission Power Control for Remote State Estimation Over Fading Channels," *IEEE Transactions on Automatic Control*, vol. 63, no. 1, pp. 85–100, Jan 2018.