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Model-Based Network Scheduling and Control for Systems over the IEEE 802.15.4 Network*

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Abstract The scheduling and control of a class of wireless networked control system is investigated, whose control loop is closed via a shared IEEE 802.15.4 wireless network. By using a gain scheduler within the packet-based control framework and fitting the delay-dependent gains into a time-delay system model, a less conservative self-triggered approach is proposed to determine the sampling update, which consequently enables the design of two network scheduling algorithms to reduce the communication usage. Numerical and TrueTime based examples illustrate the effectiveness of the proposed approach in the sense that it reduces greatly the communication usage while maintaining satisfactory control performance.

Keywords IEEE 802.15.4, packet-based control, scheduling, wireless networked control system.

1 Introduction

With the rapid advance of the wireless communication technology, the data transmission channels of control systems can now be implemented with various kinds of wireless communication networks, thus forming the so-called wireless networked control systems (WNCSs). Applications of WNCSs can already be found in smart home, intelligent transportation, smart agriculture[1–3], and so forth. Furthermore, the next era intelligent systems such as Internet of Things, cyber physical systems, etc., are all demanding wireless connections among their components, hence creating great significance for the development of WNCSs. To make WNCSs

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reliably useful in practice, however, requires not only new design for the controller but also deep insight for the characteristics of the wireless communication network, which have attracted broad attention in recent years[4–9].

Considerable works have already been reported on WNCSs, which may be roughly divided into two categories. The first category of study is more from the control theory perspective. Despite the different communication constraints caused by wireless communication networks, these constraints can still be formulated as certain parameters within conventional control framework and hence conventional control approaches can still be applied, just like what have been done for conventional wired networked control systems. For example, data packet dropout in wireless networks can be described stochastically as a system parameter and the closed-loop system can then be analyzed accordingly[10, 11]; Notations of maximum allowable transfer interval and upper-bounded delay to stabilize the control system can still be identified for WNCSs[12, 13], just to name a few. Different from this traditional control approach, another category of works takes more characteristics of the wireless network into consideration, where the wireless network itself is also optimized and various communication protocols are explicitly studied together with the control systems[14–19]. By appropriately co-designing control system and wireless networks, improved system performance can then be expected. In this line of research, more wireless communication characteristics are considered, e.g., the battery consumption issue, system security, and many others[20, 21].

Within all these works on WNCSs, IEEE 802.15.4 based WNCSs have attracted particular attentions[14, 20, 22–28]. The IEEE 802.15.4 protocol is defined to support low-cost, low-speed ubiquitous communication between devices[29]. It is the basis for the Zigbee protocol which is widely used in Internet of Things applications, as well as the basis for ISA100.11a and WirelessHART which are of particular significance for industrial automations. Hence, IEEE 802.15.4 based WNCSs are particularly representative[30, 31]. We notice that existing works on IEEE 802.15.4 based WNCSs usually assume the wireless network being private to the control system, and therefore the co-design of the IEEE 802.15.4 network and the control system is much simplified. This may be interpreted as a simplified assumption of pioneering works. However, one key advantage of WNCSs is its flexibility compared with wired NCSs, i.e., devices can easily join or leave the system via wireless connections, but this advantage means a shared wireless network may be more realistic in many occasions of WNCSs. Such a shared wireless network is not dedicated to the considered control application, thus causing unpredictable communication resources to the control system and posing great challenges to the design and analysis of WNCSs.

Along this research line, we consider the scheduling and control of a class of WNCSs where the communication network is IEEE 802.15.4 based and the sensor is energy-constrained. The control inputs of the WNCS are produced by a simple gain scheduler embedded in the actuator[32]. Thus, our focus turns to designing a scheduling strategy to update the sensing data for the gain scheduler. By introducing the network-induced delay and the delay-dependent control gains into a conventional self-triggered model, a less conservative approach is first designed to calculate the update deadline. This approach lays the foundation for the design of two network schedulers. The first network scheduler, together with the gain scheduler, achieves a better control trajectory at much less energy consumption of the sensor, and the second hybrid access scheduler is designed for the particular purpose of reducing the valuable guaranteed communication resources in the IEEE 802.15.4 network.

The rest of the paper is organized as follows. The problem of interest is stated in Section 2. The mode-based network scheduling algorithm and the control strategy are discussed in Section 3. Examples are provided to illustrate the effectiveness of the proposed approach in Section 4, and the paper is concluded in Section 5.

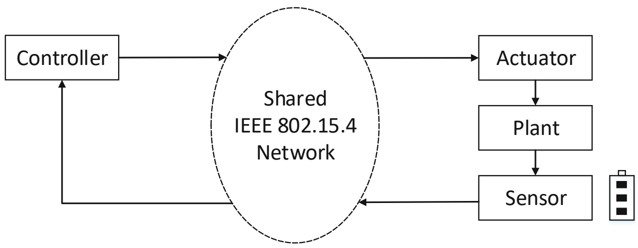
2 System Description and Problem Statement

In this work we consider a system setting as depicted in Figure 1(a), where both control channels are closed by a shared IEEE 802.15.4 network. The plant is described by a linear time invariant discrete-time system,

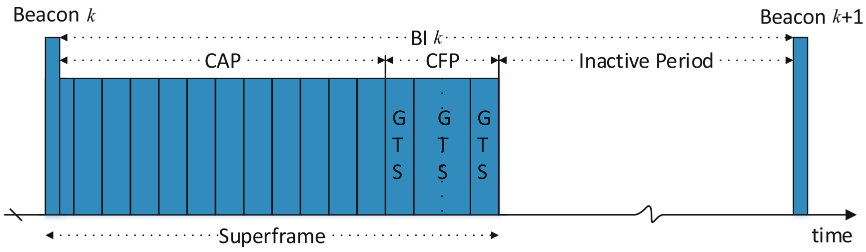
$$x(k+1) = Ax(k) + Bu(k), \tag{1}$$

where $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$, $x(k) \in \mathbb{R}^n$ is the system state and $u(k) \in \mathbb{R}^m$ is the control input, respectively. The sensor is assumed to be battery powered and therefore its energy consumption needs to be taken into account in our problem setting.

Two different medium access methods are available for the WNCS. Under the beacon-enabled mode, the PAN (personal area network) coordinator broadcasts beacons (a special data frame, as depicted in Figure 1(b)) periodically to synchronize all the associated users with itself and the time is divided into consecutive beacon interval (BI). The time synchronization of the WNCS is implemented by aligning the sampling period with the beacon interval[25]. The superframe, which is equally divided into sixteen time slots, includes the contention access period (CAP) and the contention free period (CFP). During the CAP, the users access the wireless channel according to the carrier sense multiple access/collision avoidance (CSMA/CA) mechanism. While during the CFP, the time division multiple access (TDMA) policy is adapted. To be more specific, the PAN coordinator will allocate an exclusive guaranteed time slot (GTS) for each device in advance. The optional inactive period occurs when the BI is set larger than the superframe duration, during which the entire network turns into low power mode[33].



(a) This WNCS is closed via the shared IEEE 802.15.4 network where the sensor is battery powered



(b) The beacon interval and superframe of the shared IEEE 802.15.4 network

Figure 1 The WNCS of interest

It is understood that unless extreme events of electromagnetic interference and beacon frame loss happen, the data packet transmission during the CFP period is considerably safe[29, 34], which can hence be assumed to be lossless.

The design objective of the considered system involves both the control system performance and the communication resources utilization. For the former, one may need not only guarantee a desired control trajectory but a satisfactory overall system lifetime due to the sensor energy constraint. It is known that the sensor battery is consumed on operations of listening, receiving and transmitting packet, in which listening is more expensive than transmitting[14]. In order to prolong the control lifetime, power expensive communications should be limited, especially communications via CAP due to the extra energy-consuming clear channel assessments in the CSMA/CA mechanism[35, 36].

On the other hand, the private GTS should be carefully used in a shared network: 1) The GTS wastes superframe because it occupies the superframe according to the time slot instead of the size of data packet. 2) The allocations of GTSs aggravate the contention during the CAP (page 50[29]). 3) More importantly, the number of GTS allocated in one superframe is limited up to 7 at the protocol level. Reducing the use of GTSs by the control system will benefit greatly other applications that share the wireless network.

Based on the discussions above, the problem of interest can be stated as to find an appropriate control strategy for the WNCS in Figure 1 (with the system model in (1)), which can maintain satisfactory control performance at much reduced usage of GTSs.

3 Network Scheduling and Control

In our proposed approach the conventional controller is replaced by a network scheduler and a gain scheduler, as shown in Figure 2. Instead of sending a sequence of predicted control signals to the actuator like the packet-based control approach[37], a sequence of control gains are stored in both the network scheduler and gain scheduler. With these control gains, several steps of control inputs can be produced using only one step of the sensing data. The network scheduler is designed to determine the next deadline of updating the sensing data in the gain scheduler as well as the medium access method. The gain sequence is organized as follows:

$$K = [K_1^{\mathrm{T}}, K_2^{\mathrm{T}}, \cdots, K_N^{\mathrm{T}}]^{\mathrm{T}},$$

where N is the number of control gains, which are scheduled based on the time delay from the sensor to the controller, denoted by τ_k. The control signals are calculated as follows,

$$u(k|k-\tau_k) = K_{\tau_k} x(k-\tau_k).$$

Since the gain scheduler has at most N control gains to select from, the sensing data must be updated within N time steps, i.e., $\tau_k \le N$.

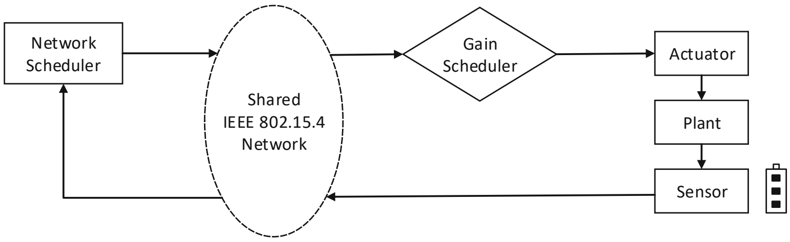


Figure 2 The WNCS with the gain scheduler and the network scheduler

3.1 Calculate the Next Update Deadline

Define the update deadline sequence (the deadline before which the sensing data must be updated in the gain scheduler) as $\{k_1, k_2, \cdots, k_i, \cdots\}$ and the control error as

$$\delta u(k) \triangleq u(k) - K_1 x(k-1), \quad k \in [k_i, k_{i+1}). \tag{2}$$

It is observed that $k_{i+1} - k_i \in [1, N]$ is the number of control signals that the gain scheduler produces with the same sensing data $x(k-1)$. If $\delta u(k) \equiv 0$, then $u(k) \equiv K_1 x(k-1) = u(k|k-1)$, which means only K_1 is scheduled and the sensing data in the gain scheduler must be updated at every time step. In this case, the next update deadline $k_{i+1} \equiv k_i + 1$ and the sensor must collect and transmit the sensing data with pair-GTS transmission (Remark 3.1) all the time. This comes to the extreme situation of the best control trajectory but maximized GTS usage. More intuitively, we combine Equations (1) and (2) to derive

$$z(k+1) = \Lambda z(k) + \Theta \delta u(k), \quad k \in [k_i, k_{i+1}), \tag{3}$$

where

$$z(k) = \begin{pmatrix} x(k) \\ x(k-1) \end{pmatrix}, \quad \Lambda = \begin{pmatrix} A & BK_1 \\ I & 0 \end{pmatrix}, \quad \Theta = \begin{pmatrix} B \\ 0 \end{pmatrix},$$

and $I \in R^{n \times n}$ is the identity matrix. The control error (2) becomes the control input of this augmented equation (3), which has an ISS (input-to-state stability) Lyapunov function if Λ is a Schur matrix[38]. With this observation, we obtain the criterion as done in [39]. For all control input of the WNCS, the following predefined condition should be satisfied, i.e.,

$$\forall k > 0, \quad ||\delta u(k)|| \le \mu ||z(k)||, \tag{4}$$

where $0 < \mu$ is a tuning threshold. For all control signals that the gain scheduler produces with sensing data $x(k_i - 1)$ during the update deadline interval, we expect

$$||u(k|k_i - 1) - K_1 x(k-1)|| \leq \mu ||z(k)||, \quad \forall k \in [k_i, k_{i+1}).$$

Thus, the next update deadline can be determined by the first control signal that violates the condition in (4), i.e.,

$$\begin{aligned} k_{i+1} = &\min\{\varsigma | \varsigma \in \mathbb{N}, k_i \leq \varsigma \leq k_i + N - 1, \\ &||u(\varsigma | k_i - 1) - K_1 x(\varsigma - 1)|| > \mu ||z(\varsigma)||\}. \end{aligned} \tag{5a}$$

If no control signals violate the condition, then

$$k_{i+1} = (k_i + N - 1) + 1 = k_i + N. \tag{5b}$$

However, the above strategy is difficult to implement in practice because $z(k)$ is unknown in real-time. In this work, we turn to a solution based on the received sensing data and previous control input recorded by the network scheduler. (5) is then revised as follows:

$$\begin{aligned} k_{i+1} = \max\{&\varsigma + 1 | \varsigma \in \mathbb{N}, k_i \leq \varsigma \leq k_i + N - 1, \delta\widehat{u}^{\mathrm{T}}(\varsigma)\delta\widehat{u}(\varsigma) \\ &\leq \mu^2(\widehat{x}^{\mathrm{T}}(\varsigma)\widehat{x}(\varsigma) + \widehat{x}^{\mathrm{T}}(\varsigma - 1)\widehat{x}(\varsigma - 1))\}, \end{aligned} \tag{6}$$

where

$$\begin{aligned} &\widehat{x}(k_i) = Ax(k_i - 1) + Bu(k_i - 1), \\ &\widehat{x}(\varsigma) = A^{\varsigma - k_i}\widehat{x}(k_i) + \sum_{j=1}^{\varsigma - k_i} A^{\varsigma - k_i - j} B K_j x(k_i - 1), \\ &\delta\widehat{u}(\varsigma) = K_{\varsigma - k_i + 1} x(k_i - 1) - K_1 \widehat{x}(\varsigma - 1). \end{aligned}$$

Remark 3.1 Just as its name implies, the pair-GTS transmission uses two GTSs of the same super-frame to transmit the sensing data over the two WNCS channels. More specifically, sensor sends the sensing data to the network scheduler with the first GTS, then the network scheduler transfers the same data to the gain scheduler with the second GTS. Thus, the round-trip network-induced delay by pair-GTS transmission is almost one step and the control inputs that the gain scheduler produces with sensing data $x(k)$ are firstly applied at time $k + 1$[25]. That is why we introduce one step delay for the sensing data in (2).

Remark 3.2 It is worth mentioning that the first control signal $u(k_i|k_i - 1)$ produced by the gain scheduler always satisfies the condition in (4) whatever value the threshold is. In other words, we always have $k_{i+1} - k_i \geq 1$.

3.2 Scheduling with Only GTS

While the update deadline k_{i+1} is determined by the network scheduler, the sampling deadline (i.e., $k_{i+1} - 1$) for the sensor to collect new sensing data is also determined. However, the sensor knows nothing about the sampling deadline, nor the time instant to collect and transmit the data. To deal with this problem, a request message must be delivered from the network scheduler to the sensor. Under the beacon mechanism, this can be implemented without adding additional overhead to the wireless network[24, 40].

In this work, the first bit of the beacon payload field, which is an optional sequence octets of the beacon frame, is set as the flag bit to encode the request message and the network scheduler operates the flag bit with the rule $\mathscr{R}(k_i - 1)$ defined as

$$\mathscr{R}(*) : \forall k > 0, \sigma(k) = \begin{cases} 1, & \text{if} \quad k = *, \\ 0, & \text{otherwise}, \end{cases}$$

where $\sigma(k)$ is the state of flag bit at time k.

While the beacon is broadcasted by the PAN coordinator, the carried request message is also sent out. When the sensor receives the beacon, it checks the flag bit to identify the request message. If $\sigma(k) = 1$, which means that the network scheduler is requesting the sensing data, the sensor then collects and transmits the sensing data, and otherwise the sensor switches to the low power mode.

It is observed that the request message is delivered exactly by the sampling deadline with the rule $\mathscr{R}(k_i - 1)$, which reduces the transmissions of the WNCS to the utmost but requires highly reliable transmissions. In this case, the sensing data at each step is transmitted with the pair-GTS transmission. Namely, the scheduling with only GTS uses least communications and no clear channel assessments, much energy-efficient for the sensor.

The above discussion is organized as the following algorithm, with the block diagram of the closed-loop WNCS being illustrated in Figure 3.

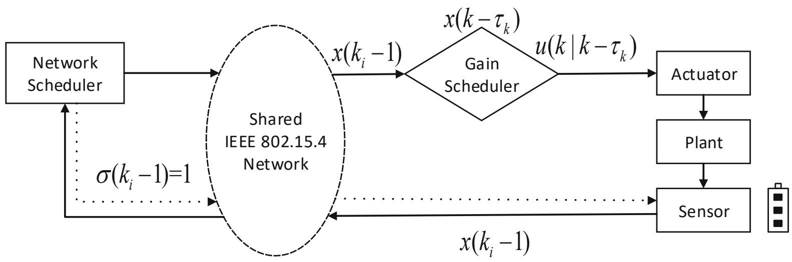


Figure 3 Scheduling with only GTS. In this case, new sensing data arrives at the gain scheduler exactly by the update deadline k_i and the network-induced delay is always 1

Remark 3.3 The GTS field in the beacon frame is used to deliver the GTS allocation information from the PAN coordinator to the sensor, which actually plays the role of the flag bit as discussed above[33]. However, the flag bit is still necessary because the sensor may transmit not only with the GTS but also via the CAP, which will be discussed in what follows.

3.3 Hybrid Access Scheduling: Further Reduction of GTS Usage

The reliability of GTS makes it possible for the network scheduler to schedule the transmission by the sampling deadline in Algorithm 1, thus reducing greatly the communication demand of the control system. This, to the contrary, implies that Algorithm 1 is not optimal in terms of GTS usage. In this subsection, we design a hybrid access network scheduling algorithm to reduce the GTS usage by using more CAP before the sampling deadline (called CAP horizon hereafter).

Algorithm 1 Scheduling with only GTS

1) Initiation. Given $k = 0$, $k_1 = 1$ and $u(0)$. $x(0)$ is transmitted with pair-GTS transmission. The network scheduler receives $x(0)$ and calculates k_2 according to (6).

2) The network scheduler sets the flag bit with rule $\mathscr{R}(k_i - 1)$, and $x(k_i - 1)$ is sent with pair-GTS transmission. The network scheduler receives $x(k_i - 1)$ and calculates k_{i+1} according to (6).

3) The gain scheduler receives $x(k_i - 1)$ and produces the control inputs for the actuator, namely $\forall\ k \geq k_i$, $u(k) = u(k|k_i - 1)$, until new sensing data arrives.

For example, when the sampling deadline for the hybrid access scheduling is $k_j - 1$ and CAP horizon is 1, then the sensor is requested to send $x(k_j - 2)$ via the CAP during the BI $k_j - 2$ (Figure 1(b)). If the transmission fails, then $x(k_j - 1)$ is requested and the pair-GTS transmission occurs in the following BI; else (i.e., the transmission succeeds), the network scheduler transfers $x(k_j - 2)$ to the gain scheduler with the GTS during the BI $k_j - 1$ and completes a sensing data update for the gain scheduler.

The CAP and GTS are not scheduled in the same BI because of the uncertainty of the CAP transmission. In this case, the WNCS is closed with a CAP during the BI $k_j - 2$ and a GTS during the BI $k_j - 1$ (Table 1, CAP-GTS-1 scheme). The sensing data arrives at the gain scheduler with two steps of network-induced delay (Table 2) which means the control signals produced by the gain scheduler will be based on a sensing data with two steps of network-induced delay. Therefore, the control signals evaluated in (5) should be replaced with $u(\varsigma|k_j - 2)$. For the CAP-GTS-1 transmission scheme, the network scheduler calculates the next update deadline as follows,

$$\begin{aligned} k_{j+1} = \max\{&\varsigma + 1 | \varsigma \in \mathbb{N}, k_j \leq \varsigma \leq k_j + N - 2, \\ &||u(\varsigma|k_j - 2) - K_1 \widehat{x}(\varsigma - 1)|| \leq \mu ||\widehat{z}(\varsigma)||\}, \end{aligned} \tag{7}$$

where $u(\varsigma|k_j - 2) = K_{\varsigma - k_j + 2} x(k_j - 2)$ and $\widehat{z}(\varsigma) = [\widehat{x}^{\mathrm{T}}(\varsigma), \widehat{x}^{\mathrm{T}}(\varsigma - 1)]^{\mathrm{T}}$ is calculated according to model evolution based on $x(k_j - 2)$, $u(k_j - 2)$ and $u(k_j - 1)$ similar to (6). It is noteworthy that the inequality $k_{j+1} - k_j \geq 1$ (Remark 3.2) is no longer guaranteed in (7) because the first control signal $u(k_j|k_j - 2)$ may violate the condition (4) when the threshold μ is set too small.

Take one step further, set the CAP horizon be 2, and then the sensor may be requested to send $x(k_j-3)$ via the CAP. In this case, the WNCS is closed with four kinds of transmission schemes (Table 1), where the CAP-CAP scheme can dramatically reduce GTS when the contention during CAP becomes slight. Similar to (7), the calculation of the next update deadline in the CAP-CAP scheme becomes

$$\begin{aligned} k_{j+1} = &\max\{\varsigma+1|\varsigma\in\mathbb{N}, k_j-1\leq\varsigma\leq k_j+N-3, \\ &||u(\varsigma|k_j-3)-K_1\widehat{x}(\varsigma-1)||\leq\mu||\widehat{z}(\varsigma)||\}, \end{aligned} \tag{8}$$

where ς begins at k_j-1 because the sensing data $x(k_j-3)$ arrives at the gain scheduler at time k_j-1 in the CAP-CAP scheme (Table 2). In a similar way, the calculation of the next update deadline in the CAP-GTS-2 scheme is

$$\begin{aligned} k_{j+1} = &\max\{\varsigma+1|\varsigma\in\mathbb{N}, k_j\leq\varsigma\leq k_j+N-3, \\ &||u(\varsigma|k_j-3)-K_1\widehat{x}(\varsigma-1)||\leq\mu||\widehat{z}(\varsigma)||\}. \end{aligned} \tag{9}$$

Table 1 Transmission schemes

Schemes	CAP horizon		Sampling deadline
	BI k_j-3	BI k_j-2	BI k_j-1
CAP-CAP	CAP	CAP	
CAP-GTS-2	CAP		GTS
CAP-GTS-1		CAP	GTS
pair-GTS			GTS, GTS

Table 2 Arrival time and network-induced delay of the sensing data in different transmission schemes

Schemes	Arrival time (k_j^*)	Network-induced delay (τ_j^*)
CAP-CAP	k_j-1	2
CAP-GTS-2	k_j	3
CAP-GTS-1	k_j	2
pair-GTS	k_j	1

The detailed procedure of the hybrid access network scheduling strategy is organized as Algorithm 2, and the block diagram of the corresponding closed-loop WNCS is shown in Figure 4.

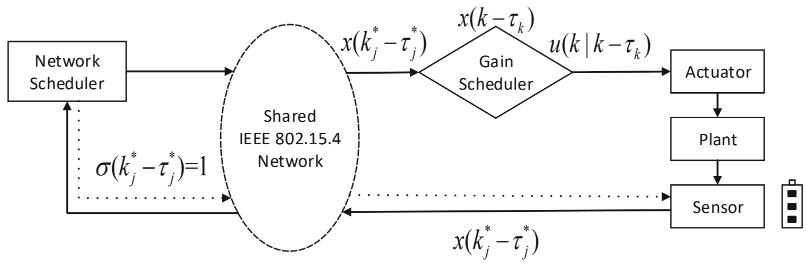


Figure 4 The block diagram of WNCS with the hybrid access scheduling algorithm, where k_j^* denotes the time that the sensing data arrives at the gain scheduler and τ_j^* is the corresponding network-induced delay (Table 2)

Algorithm 2 Hybrid access scheduling

1) Initiation. Given $k = 0$, $k_1 = 1$ and $u(0)$. $x(0)$ is transmitted with pair-GTS transmission. Calculates k_2 and $g_1 = k_2 - k_1$ according to (6).

2) Requests sampling according to g_{j-1} and completes a sensing data update for the gain scheduler.

2.1) Sets the flag bit with rule $\mathscr{R}(k_j - 3)$ and sensor sends $x(k_j - 3)$ via CAP. If the transmission fails, go to 2.2); Else, calculates k_{j+1} and $g_j = k_{j+1} - (k_j - 1)$ according to (8). If $g_j = 0$, go to 2.2); Else, transfers $x(k_j - 3)$ via another CAP. If the transmission fails, calculates k_{j+1} and $g_j = k_{j+1} - k_j$ according to (9). If $g_j \geq 1$, transfers $x(k_j - 3)$ via GTS. Else, go to 2.3).

2.2) Sets the flag bit with rule $\mathscr{R}(k_j - 2)$ and sensor sends $x(k_j - 2)$ via CAP. If the transmission succeeds (then calculates k_{j+1} and $g_j = k_{j+1} - k_j$ according to (7)) and $g_j \geq 1$, transfers $x(k_j - 2)$ with GTS; Else, go to 2.3).

2.3) Sets the flag bit with rule $\mathscr{R}(k_j - 1)$ and $x(k_j - 1)$ is transmitted with pair-GTS transmission. Calculates k_{j+1} and $g_j = k_{j+1} - k_j$ according to (6).

3) The gain scheduler receives $x(k_j^* - \tau_j^*)$ and produces the control inputs for the actuator, namely $\forall\ k \geq k_j^*$,$u(k) = u(k|k_j^* - \tau_j^*)$, until new sensing data arrives.

Remark 3.4 In the CAP-CAP scheme, the gain scheduler will send back an acknowledgment frame to the network scheduler to confirm successful transmission via the second CAP (page 105[29]).

Remark 3.5 It is noticed that the sensing data arrives at the gain scheduler one step earlier than update deadline in the CAP-CAP scheme. Moreover, the uncertainty of transmissions via CAP introduces extra delay to the control inputs which degrades the control performance. This defect is compensated for with a smaller update deadline interval under the constraint (4). Generally speaking, a larger CAP horizon means not only much more complicated scheduling procedure but also a smaller sampling interval and thus more consumption of the sensor battery. Therefore, we only discuss the CAP horizon of 2 such that the CAP-CAP transmission scheme is exactly included.

3.4 Closed-Loop Stability and Stabilization

The stability of the control strategy is analyzed within the classic time delay systems framework. The closed-loop of the WNCS is essentially a time delay switched model, i.e.,

$$x(k+1) = Ax(k) + BK_{\tau_k}x(k-\tau_k), \quad \tau_k \in \Omega, \tag{10}$$

where $\Omega = \{1, 2, \cdots, N\}$.

Based on the time delay system theory, the stability condition of the closed-loop system in (10) is given without proof since it can be done similarly as in [41].

Theorem 3.6 *Given $\lambda \geq 1$ and control gains $K_i, i \in \Omega$. The closed system* (10) *is stable if there exist $P_i = P_i^{\mathrm{T}} > 0$, $Q_i = Q_i^{\mathrm{T}} > 0$, $R_i = R_i^{\mathrm{T}} > 0$, and $S_i = \begin{pmatrix} S_i^{11} & S_i^{12} \\ * & S_i^{22} \end{pmatrix} \geq 0$, T_i^1, T_i^2 with proper dimensions such that the following condition are satisfied:*

1) $\forall i \in \Omega$,

$$\Phi_i = \begin{pmatrix} \Phi_i^{11} & \Phi_i^{12} & (A-I)^{\mathrm{T}}H_i \\ * & \Phi_i^{22} & (BK_i)^{\mathrm{T}}H_i \\ * & * & -H_i \end{pmatrix} < 0,$$

$$\Psi_i = \begin{pmatrix} \lambda S_i^{11} & \lambda S_i^{12} & \lambda T_i^1 \\ * & \lambda S_i^{22} & \lambda T_i^2 \\ * & * & R_i \end{pmatrix} \geq 0;$$

2) $\forall i, j \in \Omega$,

$$P_i \leq \lambda P_j, \quad Q_i \leq \lambda Q_j, \quad R_i \leq \lambda R_j,$$

where

$$\begin{aligned}
&\Phi_i^{11} = (\lambda - 1)P_i + Q_i + 2\lambda P_i(A - I) + T_i^1 + (T_i^1)^{\mathrm{T}} + iS_i^{11}, \\
&\Phi_i^{12} = \lambda P_i BK_i - T_i^1 + (T_i^1)^{\mathrm{T}} + iS_i^{12}, \\
&\Phi_i^{22} = -T_i^2 - (T_i^2)^{\mathrm{T}} + iS_i^{22}, \\
&H_i = \lambda P_i + NR_i.
\end{aligned}$$

Based on the stability result above, the following nonlinear minimization problem is derived by matrix transformation and cone complementarity linearization[42]. We omit the detailed proof process of the following theorem since it can be similarly done as in [42], to which interested readers may refer.

Theorem 3.7 *Given $\lambda \geq 1$. $\forall i, j \in \Omega$, define the following nonlinear minimization problem $\mathcal{P}_i$ with linear matrix inequality conditions*

$$\mathcal{P}_i : \begin{cases} \min & Trace\ (Z_i R_i + L_i P_i + M_i Q_i) \\ \text{s.t.} & L_i = L_i^{\mathrm{T}} > 0, \quad M_i = M_i^{\mathrm{T}} > 0, \quad W_i = W_i^{\mathrm{T}} > 0, \\ & L_i \leq \lambda L_j, \quad M_i \leq \lambda M_j, \quad W_i \leq \lambda W_j, \\ & X_i = \begin{pmatrix} X_i^{11} & X_i^{11} \\ * & X_i^{22} \end{pmatrix} \geq 0, \\ & \Phi_i < 0, \quad \Psi_i' \geq 0, \quad \Theta_i^1 \geq 0, \quad \Theta_i^2 \geq 0, \quad \Theta_i^3 \geq 0, \quad \Theta_i^4 \geq 0, \end{cases}$$

where

$$\Phi_i' = \begin{pmatrix} \Phi_i^{11'} & \Phi_i^{12'} & \lambda L(A-I)^{\mathrm{T}} & NL(A-I)^{\mathrm{T}} \\ * & \Phi_i^{22'} & \lambda(BV_i)^{\mathrm{T}} & N(BV_i)^{\mathrm{T}} \\ * & * & -\lambda L_i & 0 \\ * & * & * & -NM_i \end{pmatrix},$$

$$\Psi_i' = \begin{pmatrix} \lambda X_i^{11} & \lambda X_i^{12} & \lambda Y_i^1 \\ * & \lambda X_i^{22} & \lambda Y_i^2 \\ * & * & Z_i \end{pmatrix},$$

$$\Theta_i^1 = \begin{pmatrix} R_i & P_i \\ * & Q_i \end{pmatrix}, \quad \Theta_i^2 = \begin{pmatrix} Z_i & I \\ * & R_i \end{pmatrix},$$

$$\Theta_i^3 = \begin{pmatrix} L_i & I \\ * & P_i \end{pmatrix}, \quad \Theta_i^4 = \begin{pmatrix} M_i & I \\ * & Q_i \end{pmatrix}.$$

If $\forall i \in \Omega$, the solution of $\mathcal{P}_i$ is $3n$, then the closed loop system (10) is stabilizable with the gain sequence $K = [(V_1 L_1^{-1})^{\mathrm{T}}, (V_2 L_2^{-1})^{\mathrm{T}}, \cdots, (V_N L_N^{-1})^{\mathrm{T}}]^{\mathrm{T}}$.

4 Simulation Examples

Two simulation examples are provided to illustrate the effectiveness of the proposed Algorithm 1 and Algorithm 2 respectively.

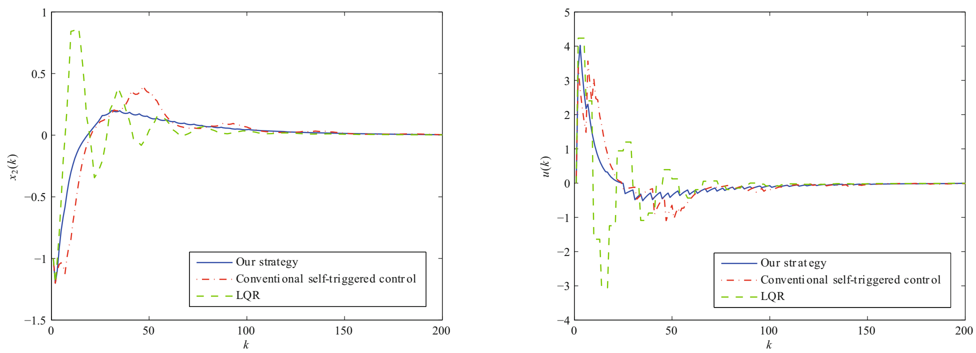
Example 4.1 Consider the system model in (1) with the following matrices which is open-loop unstable,

$$A = \begin{pmatrix} 0.98 & 0.10 \\ 0.00 & 1.20 \end{pmatrix}, \quad B = \begin{pmatrix} 0.04 \\ 0.10 \end{pmatrix}.$$

The initial sate is set as $x_0 = [-2, -1]^{\mathrm{T}}$. The control gains are calculated with the same receding horizon controller as in [37]. The weighting matrices Q, R are identity matrices with proper dimension and the control and prediction horizon N_u, N_p are set as 10 and 20 respectively.

$$K = \begin{pmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ K_5 \\ K_6 \\ K_7 \\ K_8 \\ K_9 \\ K_{10} \end{pmatrix} = \begin{pmatrix} -0.1133 & -3.1573 \\ -0.0690 & -2.6025 \\ -0.0373 & -2.1543 \\ -0.0143 & -1.7886 \\ 0.0025 & -1.4882 \\ 0.0149 & -1.2402 \\ 0.0239 & -1.0349 \\ 0.0306 & -0.8644 \\ 0.0354 & -0.7227 \\ 0.0389 & -0.6048 \end{pmatrix}.$$

Here, we set $\mu = 0.2$. The control input produced with our strategy has different control gains and variant update interval. To illustrate the effectiveness of the proposed control strategy, we compare it with other two cases: 1) Conventional self-triggered control with fixed control gain $K_{1,0}$; 2) Conventional LQR whose sampling interval is fixed with 4 steps and $K_{LQR} = [-0.2191 - 3.7958]$. The system dynamic and control inputs with these controllers are depicted in Figure 5(a) and Figure 5(b) respectively. It is shown that our approach yields better system trajectory with less data transmissions (43 compared with 48 and 51).



(a) The system dynamics with different controllers (b) The control input with different controllers

Figure 5 Comparing the proposed approach with both self-triggered controller and LQR controller

Example 4.2 In order to illustrate that the usage of GTS can be further reduced with Algorithm 2, a TrueTime-based simulation example is considered. The TrueTime 2.0 block diagram is depicted in Figure 6. Besides the GTS block and CAP block, the Beacon block simulates the transmission of request message (Subsection 3.2) and the acknowledgement (Remark 3.4) as mentioned earlier. We suppose $macBeaconOrder = 2$ (a parameter associated with the length of the beacon interval) and the bit rate of the physical layer is 250kbps, thus the BI or the discrete period is 0.0641s. The control gains K is then calculated using Theorem 3.7 according to the following discrete state-space model

$$x(k+1) = \begin{pmatrix} 1.12 & -0.057 \\ 1 & 0.52 \end{pmatrix} x(k) + \begin{pmatrix} 1 \\ 0 \end{pmatrix} u(k),$$

and the initial state $x(0) = [0.5 - 5]^{\mathrm{T}}$.

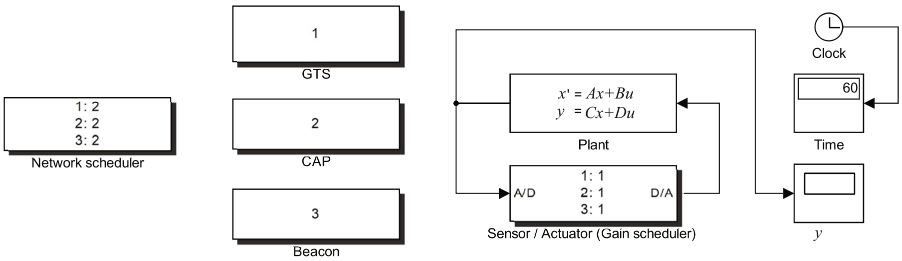


Figure 6 The TrueTime based simulation model for the considered system

We set the loss probability of CAP block (i.e., P_{CAP}) with different values and observe the corresponding number of GTS and the system dynamics. The total number of GTSs that the WNCS are used in one minute along with P_{CAP} is plotted in Figure 7 which shows that the larger the loss probability is, the more the GTS is used. $P_{CAP} = 1$ means the case of Algorithm 1. Figure 8 shows that, using Algorithm 2, the WNCSs with different loss possibilities achieve similar system dynamics.

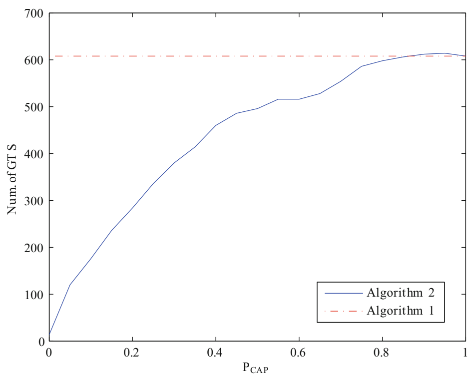
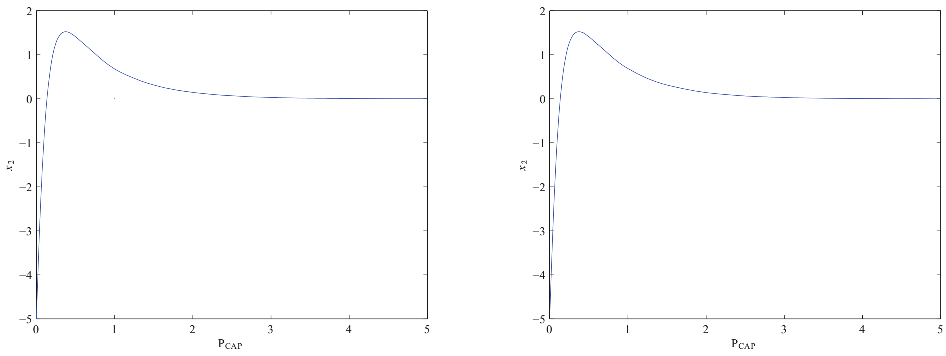


Figure 7 The number of GTSs used in one minute when the loss probability of the CAP network increases from 0 to 1



(a) $P_{CAP} = 0.4$ (b) $P_{CAP} = 0.8$

Figure 8 The dynamics of x_2 for different loss probabilities of CAP

5 Conclusions

The design and analysis of IEEE 802.15.4 wireless network based networked control control systems are considered from the perspective of maintaining satisfactory control performance while reducing as much as possible communication usage. A new control structure is proposed, consisting of a gain scheduler and a network scheduler, with two scheduling algorithms of different focuses. The use of the IEEE 802.15.4 network is a promising trend in future wireless networked control systems, and hence the design and analysis of such systems will require great attentions from the related research communities.

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