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Power Peak Shaving with Data Transmission Delays for Thermal Management in Smart Buildings

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***Abstract*—This paper presents a scheme aimed at mitigating the influence of random data transmission delays in networked thermal appliance control systems in smart buildings. The impact of this type of delays is first analyzed, and it is proposed to utilize loose timing synchronization and add blank gaps between the consecutive appliance operations to avoid the possible violation of the given power budget. A cooperative control of thermal appliance operation is developed using a networked Model Predictive Control (MPC)-based controller to deal with delays. It is also shown that the schedulability of such a control scheme can be assessed online. The performance of the proposed control scheme is assessed by a simulation study based on the thermal dynamics of an eight-room office building. The obtained results show that the proposed solution can achieve an efficient power peaks shaving in the presence of random network delays.**

***Index Terms*—Smart building, Power peak shaving, Thermal appliance control, Data transmission delay.**

I. Introduction

THE thermal appliances, also termed as thermostatically controlled loads (TCLs), in thermal management systems of buildings, such as the heating, ventilating and air conditioning (HVAC) systems, are often operated independently of each other and frequently triggered concurrently. This uncoordinated power consumption behavior of different appliances may result in high power load peaks. Consequently, in order to ensure a safe operation and an adequate level of service quality, thermal management systems have to subscribe for a high power capacity, which will result in both inefficient and expensive power consumption [1]. It is noticed that the power demand for most of TCLs is elastic [2]. Indeed, the dynamics of most TCLs are relatively slow, and usually it needs only to maintain the temperature of TCLs within a desired range. Therefore, there is a good opportunity to effectively reduce power consumption peaks by coordinating the operations of a set of TCLs.

Although much research aimed at minimizing power consumptions of TCLs have been conducted for almost a decade [3]–[6], there is still an enormous potential for improving the effect of power peak reduction. For this purpose, some architectures have been recently developed [7]–[11] on TCLs' operation control for shaving the total power load peaks while meeting the thermal constraint. However, many schemes are essentially based on synchronous operations and hence, they might fail to achieve power peak load shaving in the real-life operational environment due to, particularly, data transmission delays over the network connecting the controller with the underlying appliances. Moreover, as the most used communication technologies in building area networks (BANs), such as Ethernet, WiFi and Zigbee, are asynchronous protocols [12]–[15], data transmission delays exhibit a random nature. In addition, a more important concern on TCL is that it is operated at a much higher switch frequency during the whole day compared with electric vehicles (EVs) charge and storage management, which makes it sensitive to network delays. Consequently, TCLs that are supposed to operate in different periods may be triggered concurrently, and it would be very likely that power load peaks cannot be effectively shaved, resulting in power budget violations.

The focus of this paper is to develop a new scheme to eliminate the failure due to random network delays in TCL control systems while ensuring that the overall power capacity and the temperature constraints are respected. Specifically, the influence of the random network delays is mitigated as follows: First, we use a loose timing synchronization to approximately synchronize clocks among the controller and TCLs within an upper bounded timing error. Then, to mitigate the impact on power peaks due to network delays and synchronization errors, we introduce a concept of blank gap (i.e., the idle time) to ensure the concerted actions of TCLs. Finally, the cooperative operations of TCLs in the presence of random network delays are generated by a networked MPC-based dynamic power control scheme. A simulation study based on an eight-room office building shows that power peaks can be effectively reduced and the power constraint can be respected all the time while temperatures are maintained in a predefined comfort zone.

The main contributions of this work are threefold:

- We propose a control scheme without requiring hardware updates for TCLs management in actual systems, by adjusting the schedule of operations to mitigate the impact of random network delays in an effective manner.
- We develope a networked MPC-based controller to coordinate the operating sequences of TCLs, which can avoid power peaks induced by random network delays.
- We conduct a simulation study based on an eight-room office building, which shows that the proposed control scheme can effectively shave power peaks while keeping the temperature at all the rooms in a predefined comfort zone.

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The rest of the paper is structured as follows. Section II summarizes the impact of random network delays on TCLs management. Section III outlines the control scheme for mitigating random network delays. Setcion IV describes the control scheme with random network delays in details. Section V presents a simulation study for evaluating the effectiveness of the proposed scheme, while Section VI concludes the paper.

II. Problem Statement

Due to the asynchronous nature of communication technologies used in TCL control systems, there exist random network delays in the data transmission between the controller and TCLs. More precisely, the operation signals, sended from the controller to different TCLs at the same time will be received at different time, which is very likely to result in inefficient power peak shaving and potential power budget violation.

In order to clearly illustrate the problem, we consider a simple example involving three TCLs (i.e., air conditioners) in three different sectors of a building. Assuming that the power rate for each TCL is identical. Similarly, the disturbances of ambient air temperature, solar radiation and temperature thresholds are also the same to three sectors. Note that the controller works in a periodic manner, and TCLs can be turned ON or OFF in each period, such as 50 time steps in this example. The power load in this building is schedulable for two TCLs, i.e., power constraint is 2 units. Therefore, at most two of the three TCLs can be turned ON simultaneously at any time. In addition, the network delays of three TCLs are τ_1, τ_2 and τ_3, respectively.

A possible set of operation sequences is shown in Fig. 1, in which the time step is based on the local clock of the controller. Corresponding to the sequences, power peaks change over the time. It can be observed that the power peak reaches up to 3 units near the 150th time step, which means that it exceeds the constraint due to the existence of random network delays.

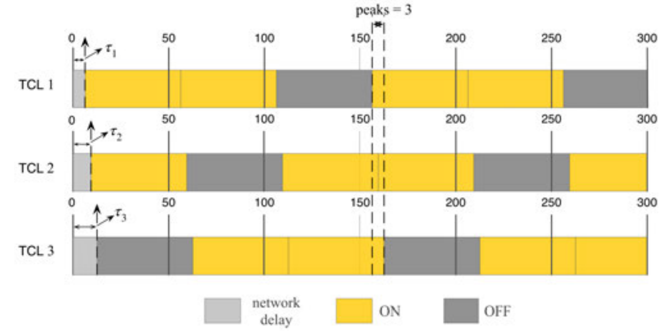

Fig. 1. ON/OFF control for three TCLs with random network delays.

In general, properly handling random network delays has a primordial importance for power peak shaving in the operation of real-life systems, and it is mainly motivated to economically guarantee the service level agreement. In fact, power suppliers tend to impose a very severe penalisation to power consumption in high peak load periods, in order to balance power production and consumption and to maintain the stability of the grid [10], [16]. Besides, as the most used communication technologies in BANs, such as Ethernet, WiFi and Zigbee, are asynchronous protocols, there exist random network delays in a real-life operational environment. Even worse, in the presence of random network delays, the schemes built upon synchronized operation sequences cannot guarantee an effective peak load shaving, which may be more critical in high peak load period. On the other hand, as TCLs are the largest energy consumers in building sectors [17] and sensitive to random delays due to high switch frequency, the efficient control of TCLs is a viable and effective solution for cost reduction. Hence, mitigating the impact of random network delays is an important issue for the smart buildings.

III. Mitigation of Random Network Delays

To mitigate the impact of random network delays in thermal management systems, we introduce a concept of blank gap. The blank gap is a time slot during which no operation will be carried out by TCLs. By adding a blank gap with suitable length between the operations of TCLs, operations can be triggered without violating the power constraint. However, as the time step is based on the local clock of the controller as shown in Fig. 1, TCLs need to know the controller's clock in order to decide the moment to trigger their operations. In conclusion, two steps are needed to mitigate the impact of random network delays: First, clocks among the controller and TCLs need to be synchronized. Second, blank gaps need to be added between the operations of TCLs.

A. Overview of Loose Timing Synchronization

In a distributed thermal management system, each TCL has its own local clock. Besides, the drift, interference of electromagnetic wave and so on can cause the deviation of the running time among TCLs [18]. Therefore, it is necessary to establish an adequate level of clock synchronization to ensure the coordinated operation of TCLs. Precise synchronization mechanisms can reach small synchronization errors in expense of high computational overhead and less robust behavior. Whereas, loose synchronization mechanisms are much less costly, while exhibiting larger synchronization errors. For cost-effectiveness, we adopt in our solution a loose timing synchronization mechanism to approximately synchronize the clocks among the controller and TCLs.

A loose timing synchronization mechanism usually uses a two-way handshake to approximately synchronize the clocks as shown in Fig. 2. Suppose that T_1 and T_4 represent the time measured by TCL's local clock when a TCL sends a synchronization request packet and receives a synchronization response packet respectively. Similarly, T_2 and T_3 represent the time measured by the controller's local clock when the controller receives a synchronization request packet and sends a synchronization response packet respectively.

According to the process of data transmission, we have:

$$T_{C2} = T_{T1} + \Delta + d, \tag{1}$$

$$T_{T4} = T_{C3} - \Delta + d, \tag{2}$$

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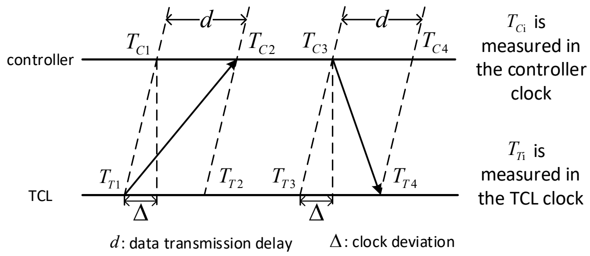

Fig. 2. Two-way handshake between the controller and the TCL.

where Δ refers to the clock deviation and d represents the data transmission delay. Then TCLs can calculate the time deviation Δ according to the information contained in the synchronization response packet so as to approximately correct its own clock:

$$\Delta = \frac{(T_{C2} - T_{T1}) - (T_{T4} - T_{C3})}{2}. \tag{3}$$

As the running time among TCLs will deviate from each other over the time, we set the system to execute timing synchronization periodically. and set the time interval between two synchronizations to be the period of sending packets from the controller. It is worth noting that there exist several industrial technologies for timing synchronization in networks [19], [20]. For example, the Network Time Protocol (NTP) can provide a synchronization accuracy at the level of 1 to 50 ms [20], which is well suited for the considered application in this work. Besides, larger synchronization errors introduced by loose timing synchronization mechanisms can be handled easily by the scheme discussed in the next section.

B. Synchronous Networked Power Peak Control

Due to the presence of random network delays and synchronization errors, power peaks are more likely to exceed the constraint. In order to avoid this situation, blank gaps are added between the ON/OFF operations, as a compromise between control effectiveness and power peak shaving. In other words, blank gaps can mitigate the impact of random network delays and synchronization errors with a slight increase of power peaks. Specifically, all blank gaps have the same length of time, and each of them is separated into two equal parts, which are inserted at the beginning and the end of each cycle time, respectively. Note that no operation will be carried out by TCLs during a blank gap (i.e., TCLs are in the OFF state).

Essentially, the control scheme of adding blank gaps will shorten the operation time of TCLs. As a result, large blank gaps will reduce the control effectiveness of TCLs, while small blank gaps will make controller tuning more complicated. A trade-off between the effectiveness and the complexity of the control scheme is to set gap time slightly larger than the optimal one, moreover, an integer is easy to understand and deploy. Based on this consideration, the gap time, ε, is set to twice the sum of the maximum network delay (i.e., $\tau_{\max}$) and the maximum synchronization error (i.e., $\delta_{\max}$):

$$\varepsilon = 2(\tau_{\max} + \delta_{\max}). \tag{4}$$

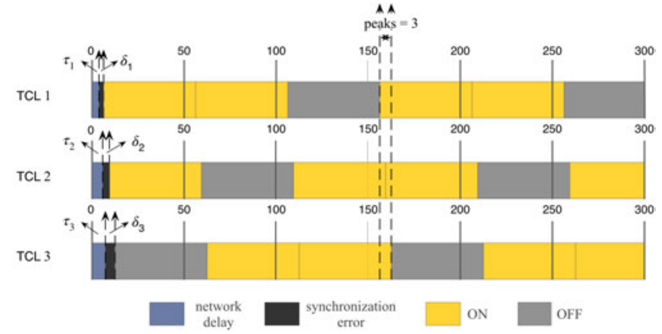

Fig. 3. ON/OFF control for three TCLs with random network delays and synchronization errors.

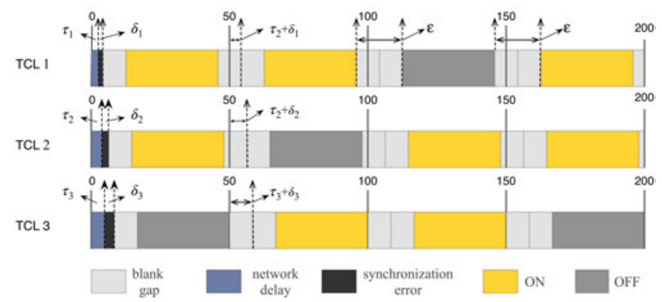

Fig. 4. ON/OFF control for three TCLs with inserted blank gaps.

This choice can assure that network delays and synchronization errors can be safely handled while the performance will not be significantly affected as long as the rate of TCL control is sufficiently slow. Nevertheless, this parameter can be tuned based on the actual operational environment. To illustrate the effect of setting blank gaps, we consider again the example with three TCLs. By comparison, the random network delays and synchronization errors are all taken into consideration in Fig. 3. The synchronization errors for three TCLs after a loose timing synchronization are supposed to be δ_1, δ_2 and δ_3, respectively. For simplicity, we sort TCLs according to the sum of their network delays and synchronization errors, which means $(\tau_1 + \delta_1) < (\tau_2 + \delta_2) < (\tau_3 + \delta_3)$. It can be seen that the power peaks are not schedulable as it exceeds the constraint due to random network delays and synchronization errors.

Figure 4 sets blank gaps to the operation sequences based on the Fig. 3. As $(\tau_3 + \delta_3)$ is the biggest one among the sums of random network delays and synchronization errors, ε is set to be $2(\tau_3 + \delta_3)$. As can be seen from Fig. 4, the power peaks can always respecting the constraint. Note that in Fig. 4, the ranges of blank gaps, network delays and synchronization errors are exaggerated to make the illustration clear.

Remark 1. *The random delays are related to attributes of the network, such as the topology, the size and the load. When these attributes have been set, we can use such tools as Network Calculus to estimate delays [21]. The magnitude of the synchronization errors can be determined based on the specific synchronous mechanism. Besides, as the dynamics of TCLs vary slowly compared to data transmission time, the period of a control operation is usually very long (i.e., 2 min*

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in the system considered in case study of this paper). Thus, the sum of the maximum network delay and the maximum synchronization error can be constrained into one period, so that our algorithm of adding blank gaps can be implemented as expected.

C. Schedulability with Random Network Delays

In order to assess the performance of the proposed scheme, we consider a thermal management system with n TCLs, and we use $budget$ to denote the power load constraint of the whole system. The power load of the system can be represented by:

$$P(t) = p_1(t) + p_2(t) + \cdots + p_n(t), \tag{5}$$

where $t \in [0, T]$, with T refers to the period of a operation, and $p_k(t)$ represents the power load required by the TCL k, with k = 1, 2, ..., n.

Definition 1. *A system is said to be budget-schedulable if there exists a safe schedule that respects $P(t) \leq budget$ for all $t \geq 0$.*

Obviously, systems that do not consider the appearance of random network delays and synchronization errors, named ideal systems, are budget-schedulable based on the prior works [9], [22]. In the presence of random network delays and synchronization errors, a sufficient condition for budget-schedulablility is given below.

Theorem 1. *Suppose that the blank gap is an idle time slot whose length is twice the sum of the maximum network delay and the maximum synchronization error, and it is separated into two equal parts which are inserted at the beginning and the end of each cycle time, respectively. Then it is always possible to adjust the operating schedule so that the total power load of the real system $P'(t)$ will meet the power load constraint:*

$$P'(t) \leq budget, \tag{6}$$

for $t \geq 0$.

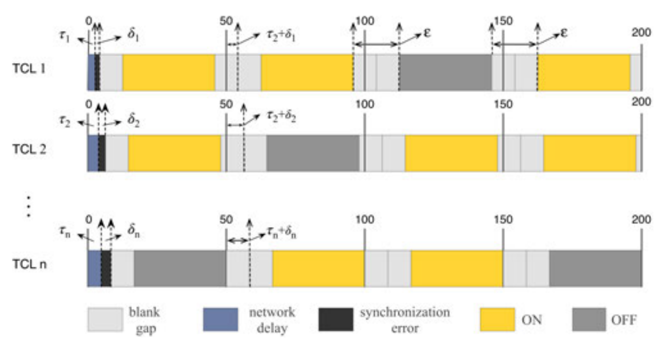

Fig. 5. ON/OFF control for n TCLs with inserted blank gaps.

Proof. We should prove that the system meets the power load constraint with the proposed scheme according to different time phases as shown in Fig. 5. As the operations of TCLs are periodic, we only need to study the system in one period. We assume that $\tau = \{\tau_1, \tau_2, \cdots, \tau_n\}$ and $\delta = \{\delta_1, \delta_2, \cdots, \delta_n\}$ are the sets of random network delays and synchronization errors for n TCLs, and we sort TCLs according to the sum of their network delays and synchronization errors, which means $0 \leq (\tau_1+\delta_1) \leq (\tau_2+\delta_2) \leq \cdots \leq (\tau_{n-1}+\delta_{n-1}) \leq (\tau_n+\delta_n)$. Then we can set $\varepsilon = 2(\tau_n + \delta_n)$. Particularly, $p_k(t)$ will be equal to zero during a blank gap time as the TCL k is in the OFF state.

If $t \in \left[0, \frac{\varepsilon}{2} + \tau_1 + \delta_1\right]$, the power load can be represented by:

$$P'(t) = 0, \tag{7}$$

obviously, $P'(t) < budget$ during this time phase.

If $t \in \left(\frac{\varepsilon}{2} + \tau_1 + \delta_1, \frac{\varepsilon}{2} + \tau_2 + \delta_2\right]$, the power load can be represented by:

$$P'(t) = p_1(t). \tag{8}$$

Generally, if $t \in \left(\frac{\varepsilon}{2} + \tau_{k-1} + \delta_{k-1}, \frac{\varepsilon}{2} + \tau_k + \delta_k\right]$, k = 2, 3, ..., n, the power load can be represented by:

$$P'(t) = p_1(t) + p_2(t) + \cdots + p_{k-1}(t), \tag{9}$$

then, according to the property of an ideal system and Definition 1, $P'(t) \leq budget$ during these time phases.

All TCLs will perform ON/OFF operations when $t \in \left(\frac{\varepsilon}{2} + \tau_n + \delta_n, T - (\frac{\varepsilon}{2} - \tau_1 - \delta_1)\right]$. The power load during this time phase is given by:

$$P'(t) = p_1(t) + p_2(t) + \cdots + p_n(t). \tag{10}$$

Similarly according to Definition 1, we can conclude that $P'(t) \leq budget$ during this time phase.

When $t \in \left(T - (\frac{\varepsilon}{2} - \tau_1 - \delta_1), T\right]$, all n TCLs will stop performing the ON/OFF operations and enter into the blank gap phases in the order of 1 to n. Generally, if $t \in \left(T - (\frac{\varepsilon}{2} - \tau_{k-1} - \delta_{k-1}), T - (\frac{\varepsilon}{2} - \tau_k - \delta_k)\right]$, $k = 2, 3, \ldots, n$, the power load can be represented by:

$$P'(t) = p_k(t) + p_{k+1}(t) + \ldots + p_n(t). \tag{11}$$

Once again we can conclude that the control system meets the power load constraint.

In conclusion, the power load of thermal management system with inserted blank gaps can be expressed as follows:

$$P'(t) = \begin{cases} 0, \quad t \in \left[0, \frac{\varepsilon}{2} + \tau_1 + \delta_1\right) \\ p_1(t) + p_2(t) + \cdots + p_{k-1}(t), \\ \qquad t \in \left(\frac{\varepsilon}{2} + \tau_{k-1} + \delta_{k-1}, \frac{\varepsilon}{2} + \tau_k + \delta_k\right] \\ p_1(t) + p_2(t) + \cdots + p_n(t), \\ \qquad t \in \left(\frac{\varepsilon}{2} + \tau_n + \delta_n, T - (\frac{\varepsilon}{2} - \tau_1 - \delta_1)\right] \\ p_k(t) + p_{k+1}(t) + \cdots + p_n(t), \\ \qquad t \in \left(T - (\frac{\varepsilon}{2} - \tau_{k-1} - \delta_{k-1}), T - (\frac{\varepsilon}{2} - \tau_k - \delta_k)\right] \end{cases} \tag{12}$$

where $k = 2, 3, \ldots, n$, $0 \leq \tau_1 \leq \tau_2 \leq \cdots \leq \tau_{n-1} \leq \tau_n$, $0 \leq \delta_1 \leq \delta_2 \leq \cdots \leq \delta_{n-1} \leq \delta_n$, and $\varepsilon = 2(\tau_n + \delta_n)$.

For each cycle, the power load can be given by (12). According to the property of an ideal system and Definition 1, it is obvious that power peaks of the system respect the power load constraint, which completes the proof. □

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TABLE I
NOTATIONS IN THERMAL DYNAMIC MODEL

Notation	Definition
T_j ($^\circ C$)	interior temperature of Sector j, i.e. the indoor air temperature
T_j^a ($^\circ C$)	ambient air temperature of Sector j
R_j^a ($^\circ C$/kW)	thermal resistances between Sector j and the ambient
R_{ij}^r ($^\circ C$/kW)	thermal resistances between Sector i and Sector j
C_j (kJ/$^\circ C$)	heat capacity of Sector j
A_j^w (m^2)	effective window area through which the solar radiation Φ_s enters
Φ_j^n (kW)	power input of the TCL n installed inside the jth sector
Φ_j^s (kW/m^2)	energy flux from solar radiation
$(\sigma_j)^2$ (-)	incremental variances of the Gauss noise
ω_j (kW)	standard Gauss noise

IV. POWER CONTROL WITH RANDOM NETWORK DELAYS

To effectively implement the algorithm with inserted blank gaps in the operating sequences, we present a thermal control model with random network delays and a schedulability test algorithm with thermal constraint in the presence of random network delays. Then, we develop a networked MPC-based controller to generate the cooperative operations involving blank gaps.

A. Thermal Control Model with Random Delays

The basic objective of the thermal control considered in this section is to ensure that the temperature of every sector is maintained in a predefined range. The thermal dynamics in a sector are mainly affected by the outside thermal energy (e.g., the solar radiation on the building's outer surface or the heat exchange with the outside ambient), the indoor thermal energy (e.g., the internal heat gains, the heat flow generated by TCLs or other equipments, as well as lights, building occupants, etc.), and the inter-sector thermal energy (e.g., the heat transported from other sectors).

For sector j with N_j TCLs (e.g., heaters or air-conditioners), the conservation law of energy gives the following simplified heat balance equation [23]:

$$\begin{aligned}\frac{dT_j}{dt} =&\frac{1}{R_j^a C_j}(T_j^a - T_j) + \frac{1}{C_j}\sum_{i=1,i\neq j}^{F}\frac{1}{R_{ij}^r}(T_i - T_j) \\ &+ \frac{1}{C_j}A_j^w\Phi_j^s + \frac{1}{C_j}\sum_{n=1}^{N_j}\Phi_j^n + \frac{1}{C_j}\sigma_j\omega_j.\end{aligned} \tag{13}$$

where the variables and parameters are defined in Table I. In this model, the system state is the indoor air temperature and the system input is the power fed into the TCLs. The disturbance includes three sources: 1) the external air temperature, 2) the energy flux from solar radiation, and 3) a third term which accounts for all other unmodeled disturbances. In parameters identification process, this last disturbance is modeled as a Gauss process.

The control input to TCL n in sector j is $u_j^n \in \{0,1\}$, where $u_j^n = 0$ corresponds to the OFF action and $u_j^n = 1$ the ON action. The corresponding power input rate is denoted by P_j^n, and the power input can be represented by:

$$\Phi_j^n = P_j^n u_j^n. \tag{14}$$

Note that as a TCL operates in the ON-OFF fashion, and considering that its dynamics are much faster than the indoor temperature variation, we assume that the power input rate is constant during the ON-cycle, equivalent to the electrical power consumption of the TCL. This assumption complies with the experimental observation reported in [23] and is suitable for the discrete-time model used below.

1) Thermal Model in State Space: We assume that $\mathcal{F} = \{1, 2, \cdots, F\}$ is a set of sectors in a building and sector j has N_j TCLs. Hence, there are in total $L = \sum_{j=1}^{F} N_j$ TCLs. Denote by $X = [T_1, T_2, \cdots, T_F]^T$ the temperature vector for F sectors, by $U_j = [u_j^1, u_j^2, \cdots, u_j^{N_j}]^T$ the control input vector for sector j with N_j TCLs, and by $U = [U_1, U_2, \cdots, U_F]^T$ the system control input vector. The disturbance in sector j is denoted by $W_j = [T_j^a, \Phi_j^s, \omega_j]^T$ and the system disturbance vector is denoted by $W = [W_1, W_2, \cdots, W_F]^T$. The state space model is then given by:

$$\dot{X} = AX + BU + DW, \tag{15a}$$

$$Y = X, \tag{15b}$$

where $A \in \mathbb{R}^{F\times F}$, $B \in \mathbb{R}^{F\times L}$ and $D \in \mathbb{R}^{F\times 3F}$ are derived from [9].

By using zero-order hold (ZOH) and assuming that the total data transmission delay is smaller than the sampling period, i.e., $0 \le \tau_k < T_s$, the discrete-time model of the system can be expressed as [24]:

$$\begin{aligned}X(k+1) =&\Phi X(k) + G_0(\tau_k)U(k) + G_1(\tau_k)U(k-1) \\ &+ H_0(\tau_k)W(k) + H_1(\tau_k)W(k-1),\end{aligned} \tag{16a}$$

$$Y(k+1) =X(k+1), \tag{16b}$$

where $X(k) \triangleq X(kT_s)$ is the system state at the kth sampling period T_s and Φ, $G_0(\tau_k)$, $G_1(\tau_k)$, $H_0(\tau_k)$, $H_1(\tau_k)$ are defined as: $\Phi = e^{AT_s}$,$G_0(\tau_k) = \int_0^{T_s-\tau_k} e^{As}Bds$, $G_1(\tau_k) = \int_{T_s-\tau_k}^{T_s} e^{As}Bds$, $H_0(\tau_k) = \int_0^{T_s-\tau_k} e^{As}Dds$, $H_1(\tau_k) = \int_{T_s-\tau_k}^{T_s} e^{As}Dds$

For notational simplicity, we define new state vectors $Z(k) = [X^T(k), X^T(k-1)]^T$, $\tilde{U}(k) = [U^T(k), U^T(k-1)]^T$ and $\tilde{W}(k) = [W^T(k), W^T(k-1)]^T$. Thus, the system (16) can be expressed as:

$$Z(k+1) = \tilde{\Phi}Z(k) + \tilde{G}(\tau_k)\tilde{U}(k) + \tilde{H}(\tau_k)\tilde{W}(k), \tag{17a}$$

$$\tilde{Y}(k+1) = Z(k+1), \tag{17b}$$

where the matrices $\tilde{\Phi}$, $\tilde{G}$, $\tilde{H}$ are defined as:

$$\tilde{\Phi} = \begin{pmatrix} \Phi & \mathbb{O}_{F\times F} \\ \mathbb{I}_{F\times F} & \mathbb{O}_{F\times F}\end{pmatrix},$$

$$\tilde{G}(\tau_k) = \begin{pmatrix} G_0(\tau_k) & G_1(\tau_k) \\ \mathbb{O}_{F\times F} & \mathbb{O}_{F\times F}\end{pmatrix},$$

$$\tilde{H}(\tau_k) = \begin{pmatrix} H_0(\tau_k) & H_1(\tau_k) \\ \mathbb{O}_{F\times F} & \mathbb{O}_{F\times F}\end{pmatrix}.$$

B. Schedulability Test with Thermal Constraint in the Presence of Random Network Delays

A fundamental question related to the power load scheduling in a building is that how much budget should be allocated for a given thermal constraint specified by a desired temperature range for every sector. A control input U for the system can be considered as a schedule that coordinates the operations through turning ON or OFF the individual TCL. We introduce below a definition of the safe schedule [9]:

Definition 2. *If U drives the temperatures in all sectors to the specified comfort zone, denoted by the set "Safe", in which the power load constraint is respected, and maintains the temperatures in that set, then the system is said to be safe and U is a safe schedule.*

We denote a feasible peak load constraint by budget and introduce a sufficient condition for the schedulability of control sequences, named as budget-schedulability as follows:

Theorem 2. *The system* (15) *is budget-schedulable if there exists a safe schedule $U = [u_j^i] \in [0,1]^L$ such that:*

1) $\sum_{j=1}^{F} \sum_{i=1}^{N_j} u_j^i P_j^i \leq \mathsf{budget}$, *and*
2) $-CA^{-1}(DW + BU) \in \mathrm{int}(\mathsf{Safe})$

Moreover, there exists a safe T_s-periodic schedule U, $T_s > 0$, for system (15).

Given the system (15), the schedulability analysis amounts then to finding a feasible peak load constraint budget that is sufficient for U to drive temperatures in all sectors to the specified comfort zone. In [9], the schedulability test algorithm is formulated as a constrained optimization problem involving all TCLs in the building as follows:

$$\min_{u} \sum_{j=1}^{F} \sum_{i=1}^{N_j} u_j^i P_j^i, \tag{18a}$$

$$\text{s.t.} \quad -CA^{-1}(DW + BU) \in \mathrm{int}(\mathsf{Safe}). \tag{18b}$$

By using linear programming to solve problem (18), we can find the minimal peak load constraint $\mathsf{budget}_{\min}$ allowing maintaining temperatures in the predefined comfort zone.

As temperatures vary very slowly, the period of TCL operation is rather long. Besides, random network delays and synchronization errors are rather small compared to the period of TCL operation. Consequently, $\mathsf{budget}_{\min}$ is indeed very close to that for an ideal system. In other words, although the control scheme of adding blank gaps will shorten operation time and boost budgets, in fact, the impact is very low due to the relatively small delays and synchronization errors. For this reason, we can use the algorithm for the ideal system to compute $\mathsf{budget}_{\min}$ for the system with random network delays.

With this scheme, the schedulability test provides a periodic solution for the system input in order to guarantee a periodic output that is within the Safe set. However, due to the varying external conditions and modeling errors, we run the schedulability test at every time period, in a receding-horizon fashion. In this way, disturbances and power budget changes can be considered in the algorithm that provides a periodic power budget validated ahead in time.

C. Networked MPC-based Thermal Control

The thermal control can be formulated as an MPC problem, which is widely used in process control applications [25], [26]. Considering the real-life operational environment, we adopt a networked MPC-based model in the system [27], [28], which can generate TCL operation sequences even with random delays. In a standard setting of networked MPC, the cost function is a weighted sum of tracking errors and control errors (i.e., the power demand) in their own prediction horizons. The networked MPC-based controller then computes the control input $U(k)$ to minimize the cost function [9]. In our system design, power demand can be minimized by penalizing each input $U(k)$, in a way that the cost function mentioned above can be interpreted as a compromise between temperature tracking errors and power demand minimization.

Generally speaking, the above networked MPC-based problem can be solved in different ways. The solution adopted in this work is least-square optimization. To apply this approach, we rewrite the system model (17) in the following form [9]:

$$Z_p(k) = \bar{Z}(k) + \bar{G}(\tau_k)U_p(k) + \bar{H}(\tau_k)W(k), \tag{19}$$

$$Y_p(k) = Z_p(k), \tag{20}$$

where the matrices $Z_p(k) \in \mathbb{R}^{FM\times 1}$, $\bar{Z}(k) \in \mathbb{R}^{FM\times 1}$, $Y_p(k) \in \mathbb{R}^{FM\times 1}$, $\bar{G}(\tau_k) \in \mathbb{R}^{FM\times LN}$, and $U_p(k) \in \mathbb{R}^{LN\times 1}$ are derived from [9].

For notational simplicity, a new vector $E \in \mathbb{R}^{FM\times 1}$ is defined as follows:

$$E(k) = Y_r(k) - \bar{Z}(k) - \bar{H}(\tau_k)W, \tag{21}$$

where the temperature reference vector $Y_r(k)$ is defined as:

$$Y_r(k) = \begin{pmatrix} Y_r(k+1|k) & Y_r(k+2|k) & \cdots & Y_r(k+M|k) \end{pmatrix}^T.$$

The considered networked MPC-based scheme can then be formulated as the following constrained optimization problem [9]:

$$\min_{U_p(k)} \left(\|\bar{G}(\tau_k)U_p(k) - E(k)\|_Q^2 + \|U_p(k)\|_R^2 \right), \tag{22a}$$

$$\text{s.t.} \quad \bar{\Psi}U_p(k) \leq \bar{\varphi}_p, \tag{22b}$$

$$\bar{G}(\tau_k)U_p(k) \leq -\bar{Z}(k) - \bar{H}(\tau_k)W + Y_u, \tag{22c}$$

$$-\bar{G}(\tau_k)U_p(k) \leq \bar{Z}(k) + \bar{H}(\tau_k)W - Y_l, \tag{22d}$$

$$U_p(k) = [u_j^i]^{LN}, \forall u_j^i \in \{0,1\}, \tag{22e}$$

where the vectors $\bar{\Psi} \in \mathbb{R}^{N\times LN}$, $\bar{\varphi}_p \in \mathbb{R}^{N\times 1}$ are derived from [9]. $Q \geq \mathbb{O}$ and $R \geq \mathbb{O}$, and the square-root matrices S_Q and S_R can be derived from $S_Q^T S_Q = Q, S_R^T S_R = R$. In the present work, Q and R are chosen as diagonal matrices. Hence, it is trivial to just take the square-root of each diagonal element. Then, a problem equivalent to (22) can be formulated as [9]:

$$\min_{U_p(k)} \left\| \begin{array}{c} S_Q C_P \bar{G} U_p(k) - S_Q Y_r(k) \\ S_R U_p(k) \end{array} \right\|^2, \tag{23}$$

subject to constraints (22b), (22c), (22d), and (22e).

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Note that it is not easy to describe such phenomena as internal heat gains, people displacement in the building, and the effect of moving electrical devices by accurate analytical models [29]. A possible solution to deal with this issue is the use of offset-free MPC control [30], which would allow rejecting the unmodeled disturbances by augmenting the system dynamics with a disturbance model in the networked MPC-based controller. Finally, we use the standard optimization solver *intvar* of the YALMIP library in Matlab to solve the problem (23).

V. Evaluations

This section presents a simulation study to evaluate the proposed scheme based on an eight-room office building. Our simulation consists of three parts: First, we introduce random network delays and synchronization errors to illustrate their impact. Then, we assess the effect of adding blank gaps to the coordinated operations. Finally, we evaluate the temperature tracking performance to make sure the thermal comfort level can be achieved.

A. Simulation Setup

The simulation study is carried out using the model of an eight-room office building, named Power FlexHouse, which is 120 m^2 large and located at Danish Technical University [23]. In this building, each room is equipped with one or two heaters, and the scheduler sends control signals to all heaters based on a star topology. Note that this small-scale example is used for the purpose of illustrating the effectiveness of our approach in an environment with random network delays. The thermal dynamics for each room use the parameters identified from measurements carried out in Power FlexHouse [23].

The configuration of the thermal conductance and power rate for each heater are drawn from [9]. The parameters of networked MPC-based controller are set to $Q(1) = \cdots = Q(M)$ = diag(10,10,10,10,10,10,10,10,10,10), M=5 and $R(1) = \cdots = R(N)$ = diag(1,1,1,1,1,1,1,1,1,1), N=5. The temperature constraint is [22,24]($^\circ C$), the sampling period is 2 minutes, i.e., $T_s = 120s$, and the total time of our simulation is 300 time steps [9].

B. Evaluations

To get the minimal power budget for heaters, we run the schedulability test algorithm. With the networked MPC-based control algorithm, we get the operating sequences of heaters. To show the impact of delays, we introduce random network delays and synchronization errors corresponding to the practical operational environments, which are all smaller than $2s$. The comparisons among the minimal budget and the power peaks with and without delays are shown in Fig. 6. It can be seen that while the total power load for the system with ideal data transmission always respects the budget [9], the total power load in the presence of random network delays exhibits spikes, which violates the power constraint.To be specific, the power peaks with random delays can be as much as 2 times higher than what is expected, which will greatly increase the operational cost.

To mitigate the impact of delays, we further evaluate the proposed control scheme with blank gaps and get the power peaks as shown in Fig. 7. It can be observed that the networked MPC-based controller with blank gaps significantly reduces power peaks, while the controller without the blank gaps exhibits occasional spikes over the allowed power constraint. Besides, the total power load controlled by the developed scheme is always under the power budget as the operation is adequately coordinated.

To evaluate the impact of blank gaps on the control effectiveness, we show the temperature tracking performance based on temperatures of all eight rooms in Fig. 8. It can be seen that the temperatures have been kept in the desired comfort range centered at 23($^\circ C$), and the tracking errors are within $\pm1(^\circ C)$. Indeed, as the sum of random network delays and synchronization errors is relatively small, the impact on control effectiveness can be ignored. Moreover, experiments show that the tracking errors in most of the rooms are kept in $\pm0.1(^\circ C)$, which confirms the high performance of our control scheme.

To accurately evaluate the impact of delays, we depict control signals and power peaks in the presence of delays between the 80th and 86th time step in Fig. 9. In the second (81st - 82nd) time step, the power peak is almost same to the case without delays except for a small lag near the 81st time step caused by delays. However, in the third (82nd - 83rd) time step, power peak violates the budget near the 82nd step because of the ON-action time overlap caused by random network delays in Room 2 and Room 7.

To better illustrate the performance of the proposed scheme, we choose the same period of control signals with blank gaps in Fig.10. As there is no operation processed during blank gaps, the spike near the 82nd step has be avoided. From the comparison of power peaks, it can be seen that the power peak with blank gaps always respects the power budget as expected.

C. Discussion

From simulations above, it is clear that the approach of adding blank gaps can easily mitigate the impact of random delays while respecting power budget and thermal constraints. Considering the efficiency of this algorithm, the random delays and synchronization errors need to be rather small compared to the period of operation, which is no more than 8.33% in the simulation. In fact, the maximum network delay cannot be more than few tens milliseconds in a BAN, while TCLs are usually operated at a time scale of more than several tens seconds. As a result, it is convincing that the proposed approach is suited for thermal management in buildings. It should be noted that the system considered in the simulations is a real building and the parameters used in the thermal model are identified from the data collected in the real-life operation of this system with high accuracy [23]. This model has been used for the fast evaluation of implementation of some control schemes [31], [32] and the results are highly reliable.

VI. Conclusion

Motivated by mitigating the impact of random network delays, this paper presented a novel scheme for thermostatically

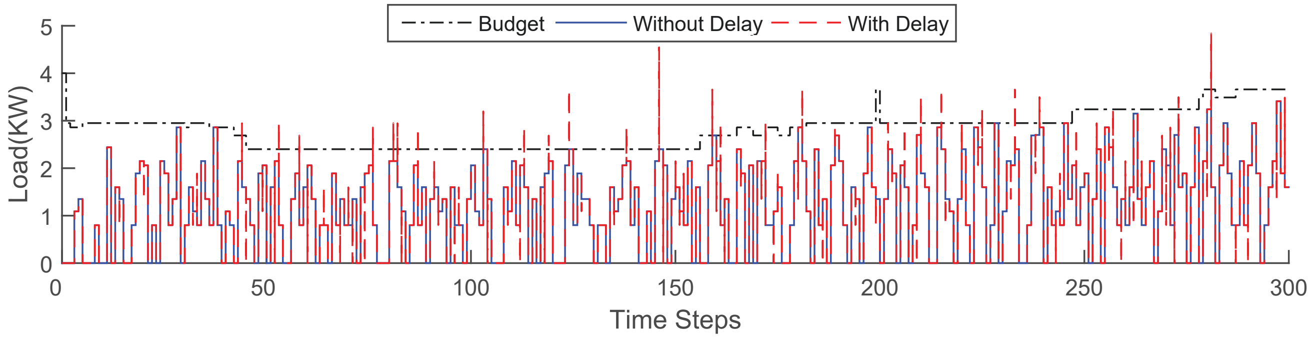

Fig. 6. Power peak comparison with/without delay.

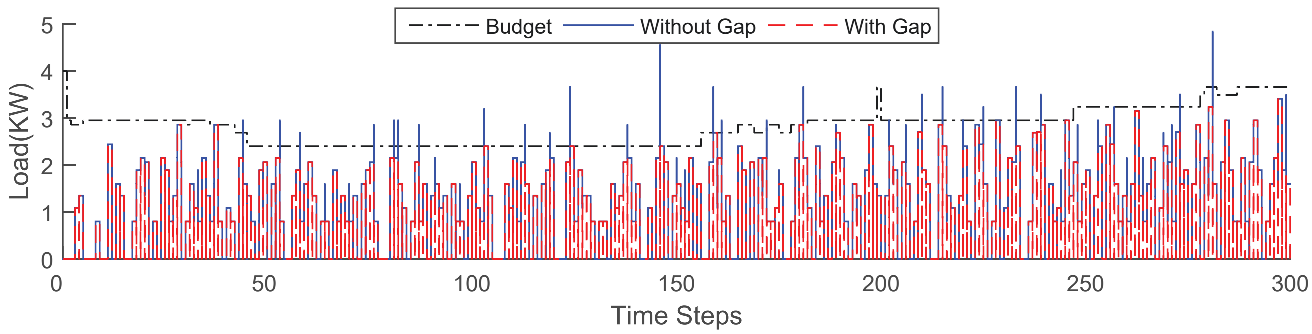

Fig. 7. Power peak comparison with/without blank gaps.

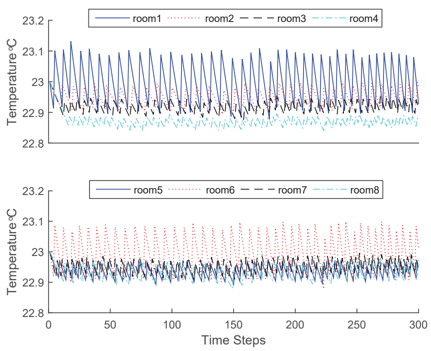

Fig. 8. Tracking temperatures using controller with blank gaps.

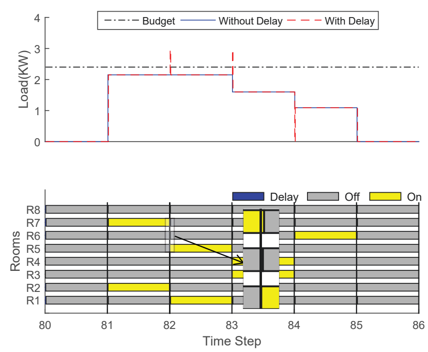

Fig. 9. The impact of delays on power peak

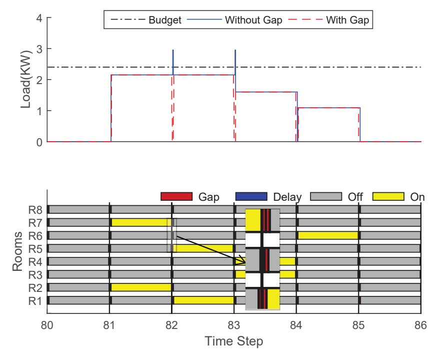

Fig. 10. The impact of blank gaps on power peak.

controlled loads control. The proposed approach consists of the use of loose timing synchronization and blank gaps to handle random network delays, and a networked model predictive control-based dynamic power control scheme to develop the coordinated operation of thermostatically controlled loads. The numerical simulation study shows that the proposed approach can effectively reduce the total power peaks, while guaranteeing a satisfactory temperature regulation performance in the presence of random network delays.

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