An optimal design method for communication topology of wireless sensor networks to implement fully distributed optimal control in IoT-enabled smart buildings

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Abstract: In smart buildings enabled by IoT technologies, wireless sensor networks (WSNs) are promising platforms to implement novel fully distributed optimal control approaches according to the edge computing paradigm. This requires knowledge from wireless communication and distributed computation fields where communication topologies are both critical. Communication topologies are designed considering network energy consumption and stability in wireless communication field, while considering optimization convergence speed in distributed computation field. But there is no inter-disciplinary design method considering these issues simultaneously. This study therefore proposes an optimal design method for communication topology of WSNs to implement fully distributed optimal control approaches. System control performance, network energy consumption and network stability are integrated into the objective function for the design. For a WSN consisting of *n* sensors, an integer programming problem with $n(n-1)/2$ design variables, i.e., elements in Laplacian matrix representing the existence of communication links, is formulated and solved by the genetic algorithm (GA). The optimal topology of a WSN, on which a fully distributed optimal control approach is implemented for optimally controlling a multi-zone dedicated outdoor air system (DOAS), is designed by the proposed method. A co-simulation testbed is constructed to test and validate the proposed method by comparing the optimal topology with different topologies. The optimal topology provides satisfactory system control performance ($CO2_{Ave}$=784 ppm, $CO2_{Max}$=916 ppm, CO_2 unmet hour=1.82 hours and E_{DOAS}=122.50 kWh), low network energy consumption (2,564.12 J/Day) and high network stability (53.90 days). The proposed method facilitates the development and applications of IoT technologies in smart buildings.

Keywords: Internet of Things (IoT), distributed optimization, communication topology design, multi-objective optimization, HVAC system, indoor air quality (IAQ).

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1. Introduction

The Internet of Things (IoT) technologies are increasingly integrated with building automation systems (BASs) to achieve the realization of smart buildings [1]. IoT devices are equipped with identifying, sensing, networking and processing capabilities, so that the advanced services can be developed over the Internet in buildings to increase their intelligence unprecedentedly. As convenient and low cost information sources, smart sensors gather data (e.g. real-time data of indoor air quality (IAQ) [2] and energy loads [3]) from the sensing field and send them to the base station, via which the occupants get access to data for better building system management. Based on the deployed real-time environmental sensors, Li et al. [2] developed control strategies for heating, ventilation and air-conditioning (HVAC) systems for the real-time improvement of IAQ. Meanwhile, Li et al. [34] developed real-time control strategies for the energy efficiency improvement of the HVAC system in office spaces. García et al. [38] investigated different wireless sensor network (WSN) deployment configurations for a soil monitoring system, i.e. soil humidity, temperature and pH monitoring. Based on that, an irrigation system determining the irrigation requirements of the fields was developed. On the other hand, computing capacities of smart sensors, which are limited though, can still make them perform as the dispersed data processing resources according to the edge computing paradigm [4]. The communication topology of WSNs is critical to fulfill these tasks. It defines the connectivity pattern in WSNs to specify with which sensors that a sensor in the network can communicate.

When WSNs are implemented for sensing applications, communication topologies have impacts on network energy consumption [39] and network stability [5]. Sensors can transmit the collected data directly to the base station, which is the direct communication. They can also transmit the data indirectly to the base station by using part of sensors as routers, which is the multi-hop routing [6]. According to the first order radio model, sensor energy consumption for data transmission and receiving is in proportion to the square or even the quartic of the distance between two nodes [7]. Generally, multi-hop routing reduces the distance a sensor must transmit/receive its data, thus is more energy efficient than direct communication. Saving sensor energy consumption is of vital importance, considering the limited energy resources available in individual sensors [8,9,36]. However, for sensors selected as routers, the energy consumption is much higher than those of the general nodes [10], and their batteries drain much quicker. Network stability, defined as the time from the beginning of the network till the death of the first node [11], is deteriorated. Designing a proper communication topology is effective to minimize network energy consumption and enhance network stability.

Receiving tremendous interests, WSNs are implemented as physical platforms for distributed optimal control in IoT-enabled smart buildings in recent years. The traditional centralized optimal control approaches are argued to be weak in scalability and reconfigurability [12]. Furthermore, the high communication burden in transmitting data to a central workstation for globally optimizing control set-points can reduce the reliability of the systems controlled [13]. These problems are increasingly serious as building systems are increasingly complex and changeable [14]. However, distributed optimal control approaches can overcome these problems [15] and are appropriate for applications in buildings [16,17]. Li and Wang [18] adopted the alternating direction method of multipliers (ADMM) to propose a multi-agent based hierarchical distributed approach for the optimal control of multi-zone dedicated outdoor air systems (DOASs). The distributed optimal control approach was implemented on IoT-based smart IAQ sensors and the smart airflow meter. Li et al. [19] proposed a real-time optimal control strategy for multi-zone variable air volume (VAV) air-conditioning systems, including three novel schemes of the temperature set-point reset scheme, the multi-objective optimization scheme and the multi-agent based distributed optimization scheme. Su et al. [20] conducted hardware-in-the-loop (HIL) simulations to implement and validate the distributed optimal control strategy on multiple wireless sensor nodes. In these studies, the global optimal control set-points are determined by the local optimization within single smart sensor in WSNs and the coordination among multiple smart sensors in WSNs. To fulfill these processes, sensors communicate with each other according to certain communication topologies. The star-connection communication topology is adopted in hierarchical distributed optimal control approaches. A central coordinating agent locates in the center, via which local agents are connected together for global information exchange [21]. In fully distributed optimal control approaches, local agents exchange information with connected peers directly [22]. Different communication topologies are adopted with more flexibility. For example, there are ring-connected topology and fully connected topology that can be adopted in fully distributed optimal control approaches. However, they are generally determined by experience, instead of a systematic design method.

Communication topologies have impacts on the convergence speed of consensus-based fully distributed optimization algorithms [23]. Zhang and Chow [24] investigated the relationship between the convergence rate of the Incremental Cost Consensus (ICC) Algorithm and the adopted communication topologies. Zhang et al. [25] investigated impacts of communication topologies on the convergence speed of a two-level consensus-based algorithm. When adopting these algorithms for fully distributed optimal control approaches, which are implemented on WSNs, local optimization and coordination at each iteration are conducted within each sampling interval of the smart sensors [26]. Consider a common condition in buildings that the sampling interval of smart sensors is one second and the optimal control interval of building systems is one minute, then the maximum iteration number is sixty. If the convergence speed is not large enough, the iteration will be stopped before reaching the convergence. Regarding this, the actual optimal control set-points for building systems will not always be found and the control performance will deteriorate. Li and Wang [27] developed a fully distributed optimal control approach for air-conditioning systems based on the two-level consensus-based algorithm. The ring-connected, the general connected and the fully connected topologies were adopted. The fully connected topology had the largest convergence speed and guaranteed to reach convergence in each optimal control interval, resulting in the best control performance. Therefore, when implementing fully distributed optimal control approaches on WSNs, a proper selection of communication topology is an effective means to improve the control performance.

Given these significant impacts, many studies made efforts to develop design methods for proper communication topologies of WSNs. In the field of wireless communication, communication topologies of WSNs are designed to reduce network energy consumption and enhance network stability. Farman et al. [28] proposed a multi-criteria based non-probabilistic technique for zone head selection in IoT-based WSNs. The zone head was responsible for collecting, aggregating and forwarding data of nodes in the same zone. The reliable and efficient nodes were selected as zone heads, leading to the improved network stability and the overall network lifespan. Based on the genetic algorithm (GA), Elhoseny et al. [29] proposed a dynamic method to determine cluster heads and form sensor clusters to extend network life. The communication topology differed after each message transmission round. On the other hand, in the field of parallel and distributed computation, communication topologies of multi-agent systems are designed to improve the convergence speed. Dai and Mesbahi [30] categorized the topology design problems into non-geometric, time-invariant geometric and time-varying geometric optimal network design. Rafiee and Bayen [31] considered the optimal topology design problem in two ways, i.e. maximize the convergence speed with the given maximum number of communication links and minimize the number of communication links with the given minimum convergence speed. Based on our preliminary analysis [32], reducing sensor energy consumption was critical when developing and implementing hierarchical distributed optimal control strategies on a battery-powered WSN. Similarly, it is also expected as a critical issue for fully distributed optimal control approaches. However, no investigation has been made on an optimal design method for communication topology of WSNs to implement fully distributed optimal control approaches, by considering network energy consumption, network stability and convergence speed (or system control performance) simultaneously, as an inter-disciplinary design method.

This study therefore proposes an optimal design method for communication topology of WSNs to implement fully distributed optimal control approaches in IoT-enabled smart buildings. This study has three major innovations. (1). By adopting knowledge and methodologies from both fields of wireless communication and parallel and distributed computation, network energy consumption, network stability and system control performance are integrated into the objective function for the optimal communication topology design problem. (2). The communication topology design of a smart sensor network, on which a fully distributed optimal control approach is implemented for optimally controlling a multi-zone dedicated outdoor air system (DOAS), is taken as an example to investigate the applicability of the proposed optimal design method. However, it is not limited to the application in smart building fields but has broad applicability to other fields with similar communication topology design problems for WSNs. (3). The optimal topology (designed by the proposed method), the ring-connected topology, the fully connected topology and the unstable topology are tested and compared, highlighting that the optimal topology outperforms other typical topologies designed by conventional methods.

The rest of the paper is organized as follows. In Section 2, the mathematical formulation of the multi-objective optimization problem for designing a communication topology of the WSN to implement fully distributed optimal control approaches is elaborated. In Section 3, the proposed approach is implemented in a targeted building WSN to design an optimal communication topology, on which a fully distributed optimal control approach is adopted for optimally controlling a multi-zone dedicated outdoor air system (DOAS). In Section 4, the performance of the proposed optimal design method is examined by comparing system control performance, network energy consumption and network stability when different communication topologies are adopted. Finally, the conclusions are presented in Section 5.

2. Optimal design problem formulation

This section elaborates the mathematical formulation of the multi-objective optimization problem for designing a communication topology of the WSN to implement fully distributed optimal control approaches. The mathematical models for estimating system control performance, network energy consumption and network stability are also elaborated.

2.1. Objective function

An outline of the proposed optimal design method is shown in Fig. 1. The objectives of optimal design problem are to maintain a satisfactory system control performance using fully distributed optimal control approaches while minimizing the network energy consumption as well as enhancing the network stability of WSNs. Using the weighted sum approach, the objective function is expressed in (1). Obj_{SysP}, Obj_{NetE} and Obj_{NetS} are the sub-objective functions concerning system control performance, network energy consumption and network stability respectively. α_{SysP}, α_{NetE} and α_{NetS} are the weighting factors. The communication topology of a WSN consisting of *n* sensors, can be modeled by the Laplacian matrix (L_n) in Fig. 2. l_{ij} is an element in the Laplacian matrix, representing the communication link between the sensor *i* and the sensor *j*. If the communication link exists between sensors *i* and *j*, l_{ij} will be -1; otherwise, l_{ij} will be 0. The undirected graph is considered in this study, thus l_{ij} equals l_{ji}. l_{ii} is calculated by summing up $-l_{ij}$ ($j=1$ to $n, j\neq i$). The shaded elements of the Laplacian matrix in Fig. 2 are the $n(n-1)/2$ design variables to be optimized. The optimal design problem for the communication topology of a WSN is transformed into an integer programming problem. When there are a large number of sensors in a WSN, which is often the case in real buildings, there will be huge number of variables to be optimized. Therefore, the genetic algorithm (GA) is adopted as the optimization algorithm to solve the optimal design problem.

$$\underset{l_{ij}=L_{n(i,j)}}{\text{Min}} \; Obj = \alpha_{SysP} \cdot Obj_{SysP} + \alpha_{NetE} \cdot Obj_{NetE} + \alpha_{NetS} \cdot Obj_{NetS} \tag{1}$$

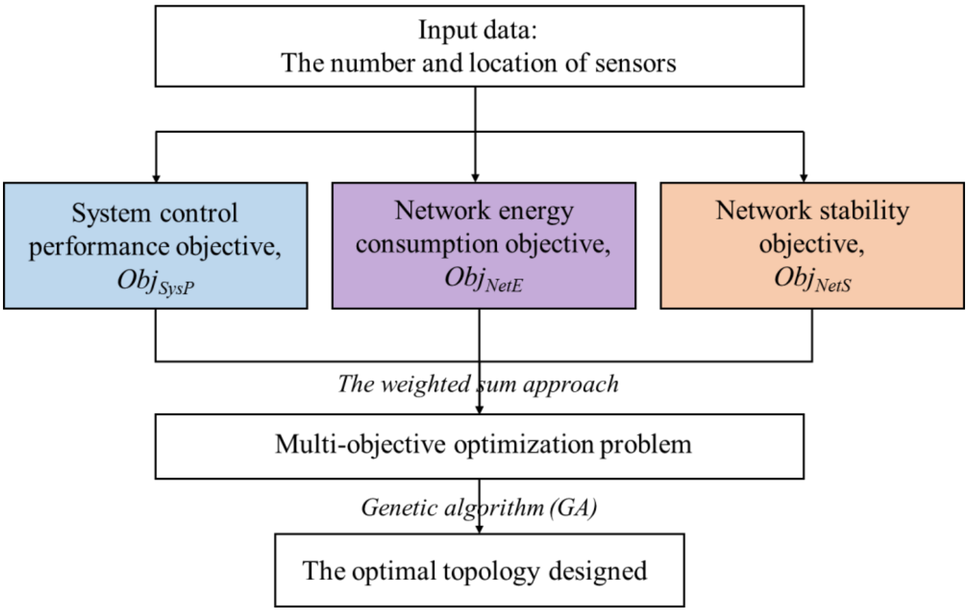

Fig. 1. Outline of the proposed optimal design method.

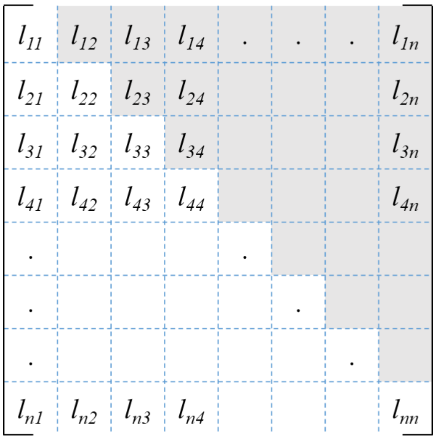

Fig. 2. The Laplacian matrix (L_n=[l_{ij}]$_{n\times n}$) of a WSN

2.2. System control performance

The algebraic connectivity, which is the second smallest eigenvalue (λ_2) of the Laplacian matrix, is a measure of the convergence speed of consensus-based distributed optimization algorithms [23]. The larger algebraic connectivity leads to a larger convergence speed [30]. Meanwhile, when implementing the fully distributed optimization algorithm on the WSN, there is higher possibility to get better system control performance, considering higher possibility to converge to the actual optimal values before reaching the maximum iteration number. The sub-objective function concerning system control performance (Obj_{SysP}) is assessed as (2).

$$Obj_{SysP} = -\lambda_2 \tag{2}$$

2.3. Network energy consumption

The network energy consumption is the sum of the total sensor energy consumption of individual sensors in a WSN. The sensor energy consumption for data transmission/receiving and data processing account for the main part of total sensor energy consumption [33]. Sensor energy consumption for data transmission/receiving ($E_{tx\&rx}$) is calculated using the first order radio model [7], as shown in (3). Where, E_{elec} is the energy dissipated to transmit or receive a message, 50 nJ/bit [7]. $\mathcal{E}_{amp}$ is the energy dissipated by the transmit power amplifier, 100 pJ/bit/m^2 [7]. d is the transmission distance. γ is the path loss exponent relating to the transmission distance. Sensor energy consumption for data processing (E_{pro}) is calculated using (4) [6]. Where, N is the number of clock cycles per task. C is the average capacitance switched per cycle, 0.67nF [6]. I_o is the leakage current, 1.196 mA [6]. n_p is a constant, 21.26 [6]. V_T is the thermal voltage, 0.2 V [6]. f is the sensor clock speed. More details can be found in the previous work by the authors of this paper [32]. Sensor energy consumption for data processing is not a function of the distance between two nodes. Changing the communication topology of the WSN has little impacts on sensor energy consumption for data processing.

Therefore, only the sensor energy consumption for data transmission and receiving is included in the sub-objective function concerning network energy consumption (Obj_{NetE}), shown as (5). It takes all sensors (i=1 to n) in the WSN into consideration. Where, $E_{tx\&rx}(i,d)$ is the energy consumption of the sensor i to transmit/receive data to/from the sensor j ($i \neq j$) with the distance of d.

$$E_{tx\&rx} = 2 \cdot E_{elec} \cdot k + \varepsilon_{amp} \cdot k \cdot d^{\gamma} \tag{3}$$

$$E_{pro} = NCV_{dd}^{2} + V_{dd}\left(I_0 e^{\frac{V_{dd}}{nV_T}}\right)\left(\frac{N}{f}\right) \tag{4}$$

$$Obj_{NetE} = \sum_{i=1}^{n}(-l_{ij}) \cdot E_{tx\&rx}(i,d) \tag{5}$$

2.4. Network stability

Since different communication topologies of the WSN have little impacts on sensor energy consumption for data processing, the standard deviation (σ) of sensor energy consumption for data transmission and receiving in the WSN is used as the sub-objective function concerning network stability (Obj_{NetS}), shown as (6). A small σ means that energy consumption for data transmission and receiving among sensors in the WSN are balanced, avoiding the concentration of much higher energy consumption on very few sensors. Therefore, the lifetime of sensors in the WSN are similar, and the network stability is enhanced. It is worthy noticing that this sub-objective function is formulated based on an assumption that the remaining battery capacity of individual sensors is similar. IoT sensors considered in this study are installed in a plug-in-play manner and they start to operate around the same time. For the same type of sensors (i.e. with the same battery capacity), the remaining battery capacity would be similar if energy consumption for data transmission/receiving and data processing was similar, which means the assumption concerned is reasonable.

$$Obj_{NetS} = \sigma \tag{6}$$

3. Implementation of the proposed optimal design approach

An office building in a Hong Kong campus [34] is selected as the targeted building, as shown in Fig. 3. A multi-zone dedicated outdoor air system (DOAS), of which the schematic is shown in Fig. 4. is assumed to be operated for this office. Outdoor air flows into the building through primary air-handling unit (PAU). Then certain amounts of outdoor air are distributed to individual rooms for a satisfactory indoor air quality (IAQ). CO_2 is one of the typical indoor pollutants, thus indoor CO_2 level is selected to evaluate IAQ in this study. For the target building in Fig. 3, there are 22 rooms, in which smart CO_2 sensors (S_1–S_{22}) are installed, are served by one PAU, on which the smart airflow meter

(S_{23}) is installed. Based on the locations of these sensors, the transmission and receiving distance (*d*) can be determined.

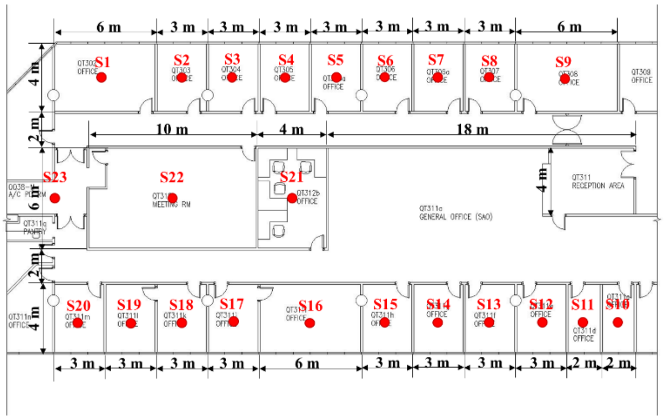

Fig. 3. Sensor locations in the targeted building

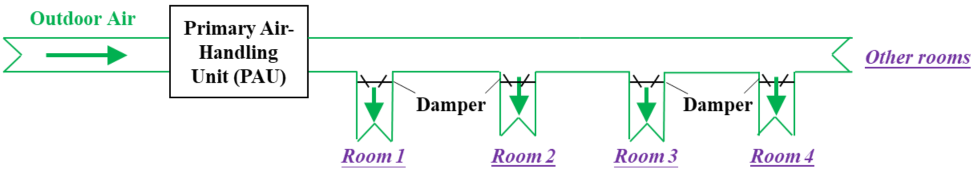

Fig. 4. Schematic of a multi-zone DOAS.

There is a trade-off when determining the amount of outdoor air volume supplied to individual rooms [18]. Larger amount of outdoor air decreases indoor CO_2 in each room, but increases the energy use in PAU for air handling and air flow delivering. Therefore, the optimal outdoor air volume set-points of individual rooms and the PAU can be determined by balancing the needs for limiting indoor CO_2 and minimizing PAU energy use. Such an optimization problem can be solved by different optimization approaches. When the fully distributed optimal control approach [35] is adopted, which is implemented on the smart sensor network, i.e. S_1–S_{23}, the communication topology of S_1–S_{23} is determined by implementing the proposed optimal design method. The weighting factors offering relatively satisfactory performance in terms of system control performance, network energy consumption and network stability are selected. By trying different combinations, α_{SysP}, α_{NetE} and α_{NetS} are 1, 1×10^3 and 8×10^5 respectively. The large difference of sub-objective weighting factors can be reduced by normalizing individual sub-objectives into same magnitude first. The optimal topology designed by the proposed method is shown in Fig. 5.

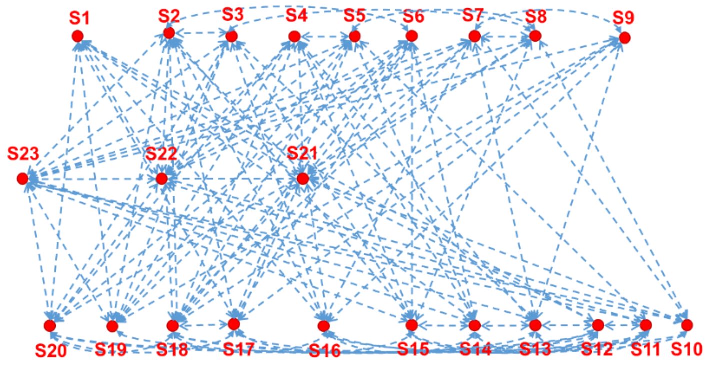

Fig. 5. The optimal topology designed by the proposed method

4. Performance analysis of the proposed optimal design method

To examine the performance of the proposed optimal design method, analysis on system control performance, network energy consumption and network stability was conducted as a trial in a typical workday, when the optimal designed topology is adopted to implement the fully distributed optimal control approach on the WSN for optimally controlling DOAS.

4.1 Test condition

The occupancy profiles in 22 rooms (R1-R22) and the outdoor weather are shown in Fig. 6 and Fig. 7. The outdoor air volume in all rooms are adjusted between 11-56 L/s. The design fan power and the design outdoor air volume of the PAU are 18.5 kW and 1,232 L/s. The PAU outdoor air volume is adjusted between 0-1,232 L/s. A TRNSYS-MATLAB co-simulation testbed is established to conduct the test case. In TRNSYS, the objective building and the DOAS are simulated to test the system control performance, including indoor CO_2 variation and energy use of the PAU, with the control set-points (i.e., outdoor air volume set-points of individual rooms and the PAU) determined from MATLAB. In MATLAB, the smart sensor network (S_1–S_{23}) are programmed, including the implemented fully distributed optimization algorithm and the sensor energy consumption model. The control set-points are optimized and sent to TRNSYS for the operation of DOAS. The sensor energy consumption is estimated to test the network energy consumption and the network stability. Both the simulation time step and the optimal control interval are one minute.

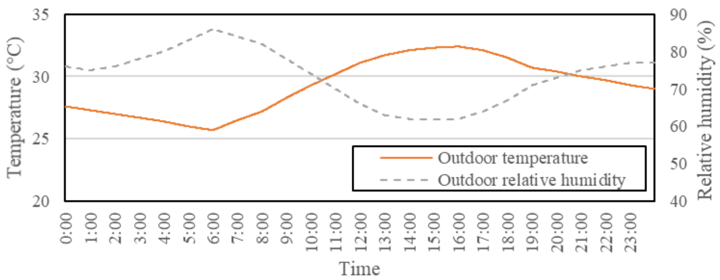

Fig. 6. Outdoor weather in the test case

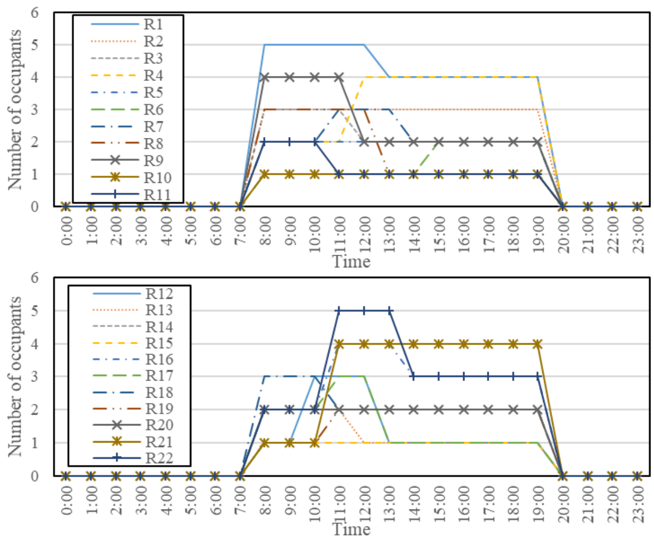

Fig. 7. Occupancy profiles in the test case

Four communication topologies, i.e., the optimal topology, the fully connected topology, the ring-connected topology and the unstable topology, for the WSN to implement the fully distributed optimal control approach are tested and compared. A description of these communication topologies is given as follows.

- **The optimal topology** is designed by the proposed optimal design method, with the objectives regarding system control performance, network energy consumption and network stability, as shown in Fig. 5.
- **The fully connected topology** is a typical communication topology, in which each sensor directly communicates with all other sensors in the WSN for information exchange, as shown in Fig. 8. The very high efficiency in obtaining global information makes its convergence speed very fast. Considering the maximum iteration number limit, there is very high possibility to converge to the actual optimal control set-points (i.e., outdoor air volume set-points of individual rooms and the PAU) and get very good system control performance. However, such a dense connected network can lead to very high network energy consumption [5].
- **The ring-connected topology** is a typical communication topology, in which each sensor can only communicate with its two adjacent neighbors directly in the WSN, as shown in Fig. 9. Low efficiency in obtaining global information makes its convergence speed slow. Considering the maximum iteration number limit, there is low possibility to converge to the actual optimal control set-points and thus the system control performance is not satisfactory. However, such a sparse connected network can lead to very low network energy consumption.

- **The unstable topology** is designed by considering the objectives of system control performance (Obj_{SysP}) and network energy consumption (Obj_{NetE}), as shown in Fig. 10. Network stability (Obj_{NetS}) is not included in the objective function of the optimal design problem. By comparing the performance given by the optimal topology and the unstable topology, the necessity to consider network stability in designing communication topology can be justified.

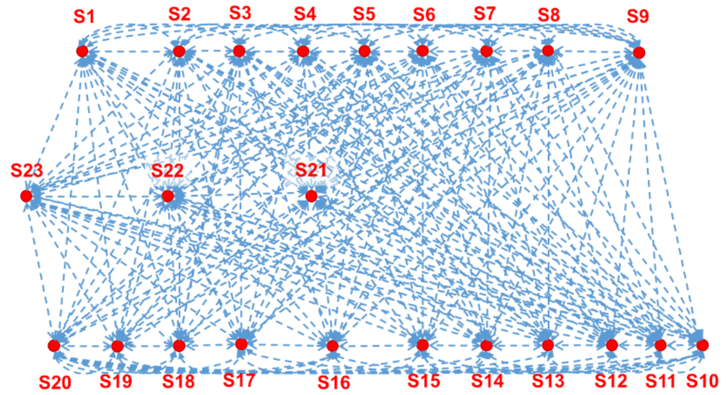

Fig. 8. The fully connected topology in the test case

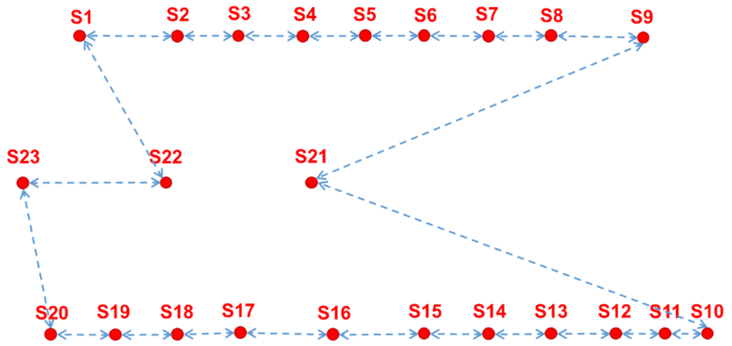

Fig. 9. The ring-connected topology in the test case

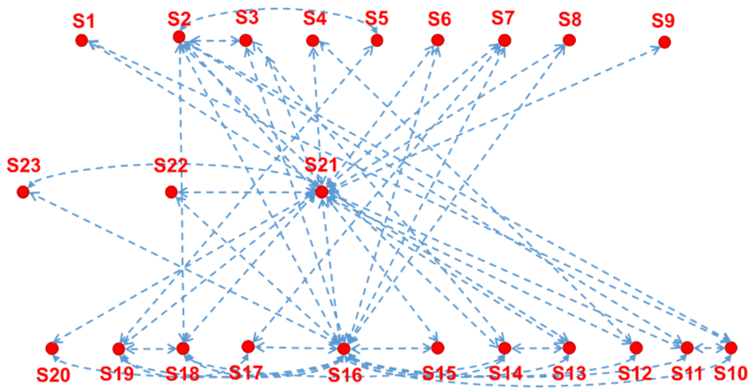

Fig. 10. The unstable topology in the test case

4.2. Performance analysis on system control performance

The algebraic connectivity of the optimal topology, the fully connected topology, the ring-connected topology and the unstable topology were 5.40, 23.00, 0.07 and 0.97 respectively. Thus the convergence speed from the highest level to the lowest level was given by adopting the fully connected topology, the optimal topology, the unstable topology and the ring-connected topology. To show the convergence process more clearly, the evolution of the outdoor air volume of individual rooms when the fully distributed optimal control approach [35] is implemented on the smart sensor network with different communication topologies are depicted in Fig. 11. They are based on a particular point of time (i.e. 10:00) as an example. The red dashed line represents the maximum iteration number, i.e. 50, corresponding to the one-minute control interval of the DOAS, the one-second sampling interval of smart sensors and the 1.2 safe factor [27]. Due to different convergence speed by adopting four communication topologies, outdoor air volume of individual rooms optimized within 50 iterations had different accuracies compared to the actual optimal outdoor air volume of individual rooms. The optimization accuracy from the highest level to the lowest level was given by adopting the fully connected topology, the optimal topology, the unstable topology and the ring-connected topology. Although the actual optimal values were not completely found within 50 iterations by adopting the optimal topology, the deviation value was negligibly small.

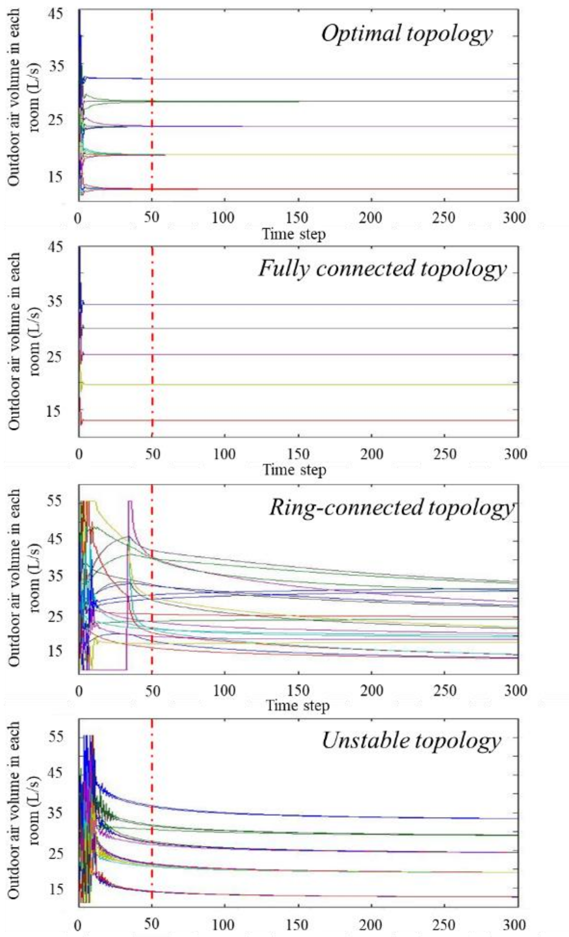

Fig. 11. Results evolution adopting different communication topologies

The control performance when the fully distributed optimal control approach is implemented on the smart sensor network with different communication topologies are summarized in Table 1, in terms of average CO_2 ($CO2_{Ave}$) during working hours (i.e. 8:00-20:00), the maximum CO_2 ($CO2_{Max}$), the CO_2 unmet hour and daily energy use of the DOAS (E_{DOAS}). The CO_2 unmet hour counts the period when indoor CO_2 exceeds 1,000 ppm, which is the upper limit recommended by the government [37]. Their control performance are evaluated by comparing with the benchmark, which is the best control performance given by the centralized optimal control approach.

- The control performance given by the optimal topology was very close to that given by the fully connected topology, which was also the closest to the benchmark among the four communication topologies (i.e. the optimal, the fully connected, the ring-connected and the unstable topologies). Specifically, both the average CO_2 were 782 ppm, the maximum CO_2 were 1,028 and 1,027 ppm, both the CO_2 unmet hour were 1.82 hours and the daily energy use of the DOAS were 122.53 and 122.50 kWh, respectively, by adopting the optimal and fully connected topologies. This indicates that adding more communication links to the network can increase the convergence speed, however, the control performance improvement can be negligibly small. Therefore, it is possible to reduce the network energy consumption and enhance the network stability by optimizing communication topologies without deteriorating the system control performance significantly.
- The control performance given by the ring-connected and the unstable topologies both deviated from the benchmark evidently. Specifically, the average CO_2 were 870 and 732 ppm, the maximum CO_2 were 1,887 and 944 ppm, the CO_2 unmet hour were 73.05 and 0 hours and the daily energy use of the DOAS were 115.98 and 141.64 kWh, respectively, by adopting the ring-connected and the unstable topologies. The control performance given by the ring-connected topology was featured with low DOAS energy use by sacrificing indoor air quality (IAQ), while the control performance given by the unstable topology was featured with very good IAQ by consuming more energy. Both of them failed to find the trade-off between a satisfactory indoor CO_2 and a minimized PAU energy use. This is due to the low possibility of converging to the actual optimal outdoor air volume of individual rooms within the preset iteration limit (i.e. 50 iterations) if adopting the ring-connected and the unstable topologies, of which the algebraic connectivity were too small, for fully distributed optimization.

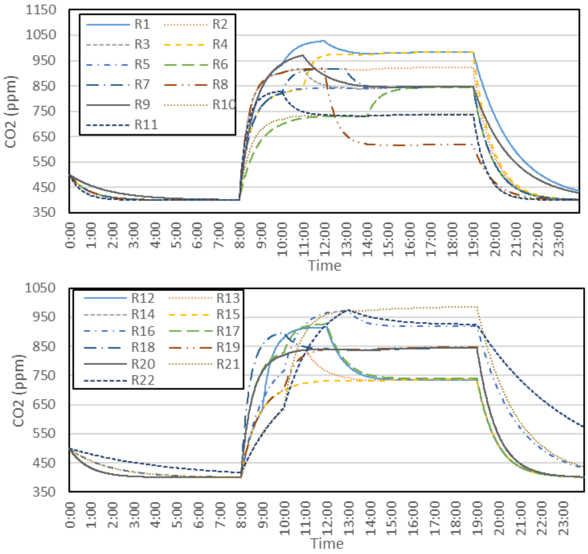

Fig. 12. CO_2 concentration in 22 rooms (R1-R22) adopting the optimal topology.

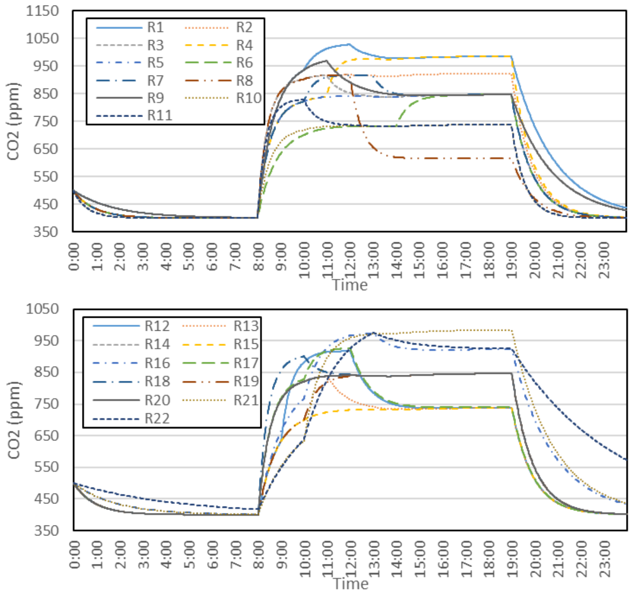

Fig. 13. CO_2 concentration in 22 rooms (R1-R22) adopting the fully connected topology.

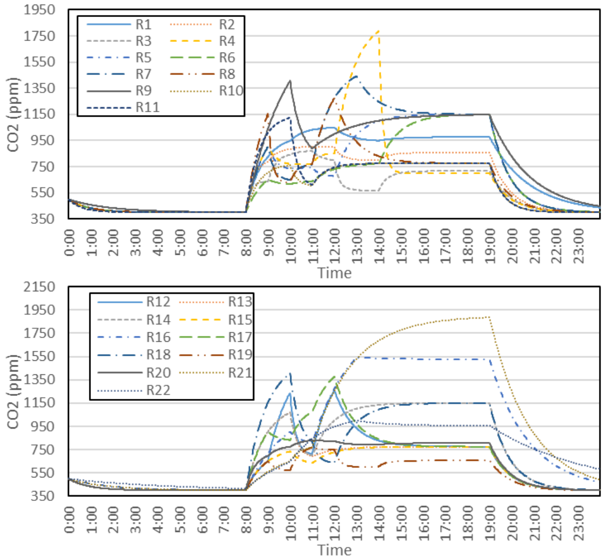

Fig. 14. CO_2 concentration in 22 rooms (R1-R22) adopting the ring-connected topology.

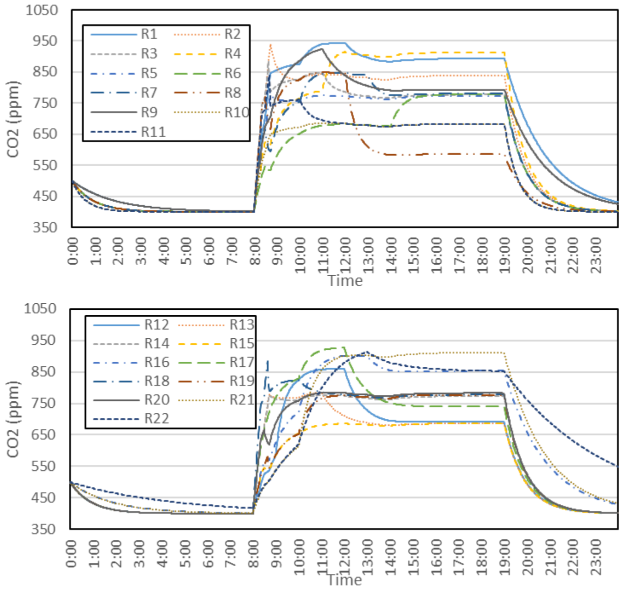

Fig. 15. CO_2 concentration in 22 rooms (R1-R22) adopting the unstable topology.

Table 1. Control performance comparison among different approaches

Optimal control approach		Control performance			
		$CO2_{Ave}$ (ppm)	$CO2_{Max}$ (ppm)	CO_2 unmet hour (h)	E_{DOAS} (kWh)
Fully distributed	Optimal topology	782	1,028	1.82	122.53
	Fully connected topology	782	1,027	1.82	122.50
	Ring-connected topology	870	1,887	73.05	115.98
	Unstable topology	732	944	0	141.64
Centralized		790	1,039	2.28	120.03

4.3. Performance analysis on network energy consumption

Fig. 16 shows the sensor energy consumption adopting different communication topologies, i.e. the optimal topology, the fully connected topology, the ring-connected topology and the unstable topology. It is worthy noticing that besides the sensor energy consumption for data transmission and receiving, the sensor energy consumption for data processing is also considered to estimate total sensor energy consumption and network energy consumption.

Communication topologies had significant impacts on sensor energy consumption for data transmission and receiving, while no significant difference on sensor energy consumption for data processing when adopting different communication topologies was observed. Specifically, when adopting the optimal topology, the sensor energy consumption for data transmission and receiving was significantly reduced compared with that adopting the fully connected topology. Sensor energy consumption for data processing were very similar when adopting the optimal, the ring-connected and the unstable topologies, but it was a little higher when adopting the fully connected topology. In the fully connected topology, additional efforts were paid to handle data directly received from all other sensors in the WSN. Higher computation complexity of the algorithms programmed in individual sensors lead to higher sensor energy consumption for data processing.

The total sensor energy consumption of individual sensors and the network energy consumption, when adopting the optimal topology, were significantly reduced compared with those adopting the fully connected topology. Total sensor energy consumption of individual sensors ranged in 102.02-150.29, 258.52-301.53, 53.93-77.75 and 56.06-220.98 J/Day when adopting the optimal, the fully connected, the ring-connected and the unstable topologies respectively. An AA size alkaline battery of 1,500 mAh was assumed to be employed in each sensor. The corresponding sensor lifetime were estimated to range in 53.90-79.39, 26.86-31.33, 104.18-150.20 and 36.66-144.49 days. For the fully connected topology, such a short battery replacement interval is neither practical nor acceptable in application. It is critical to reduce total sensor energy consumption and extend the sensor lifetime when implementing the fully distributed optimal control approach on a WSN, as expected. The optimal topology designed by the proposed method effectively extended the sensor lifetime. In addition, network energy consumption were estimated to be 2,564.12, 6,334.94, 1,686.06 and 2,399.93 J/Day when adopting the optimal, the fully connected and the ring-connected topologies respectively. Network energy consumption when adopting the optimal topology, was significantly lower than that when adopting the fully connected topology, while was a little higher than that when adopting the unstable topology.

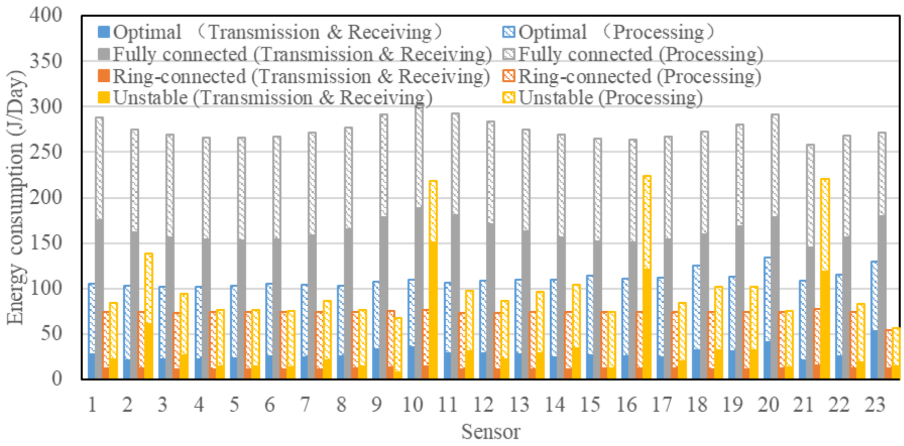

Fig. 16. Sensor energy consumption adopting different communication topologies

4.4. Performance analysis on network stability

As shown in Fig. 16, except for the unstable topology, the distribution of sensor energy consumption for data transmission and receiving among the WSN when adopting the optimal, the fully connected and the ring-connected topologies were balanced. Considering similar sensor energy consumption for data processing when adopting different communication topologies, the distribution of total sensor energy consumption among the WSN shared the same pattern with that of sensor energy consumption for data transmission and receiving among the WSN. Specifically, adopting the optimal topology, total sensor energy consumption of individual sensors among the WSN were relatively balanced. Thus lifetime of sensors in the WSN were similar. The time that the first sensor died, i.e. network stability, was 53.90 days. In contrast, adopting the unstable topology, total sensors energy consumption of individual sensors among the WSN were unbalanced. Although the network energy consumption was 2,399.93 J/Day, which was lower than that adopting the optimal topology (2,564.12 J/Day), total sensor energy consumption of a few sensors (e.g. S_{10}, S_{16} and S_{21}) were far higher than the rest sensors in the WSN. Thus lifetime of these sensors in the WSN were far shorter than the rest. The network stability was only 36.66 days. Therefore, it is crucial to include the network stability in the objective function of the optimal design problem.

5. Conclusions

An optimal design method for communication topology of WSNs to implement fully distributed optimal control approaches is proposed. System control performance, network energy consumption and network stability are integrated into the objective function for the optimal design problem. The communication topology of a WSN can be modeled by the Laplacian matrix, in which individual elements represent the existence of a communication link between any two sensors. The optimal design problem for the communication topology of a WSN consisting of *n* sensors is an integer programming problem with $n(n-1)/2$ design variables to be optimized. The Genetic algorithm (GA) is adopted as the optimization algorithm to solve the optimal design problem. The optimal topology of a smart sensor network, on which a fully distributed optimal control approach is implemented for optimally controlling a multi-zone DOAS, is designed by the proposed method. The optimal, the fully connected, the ring-connected and the unstable topologies are tested in the established TRNSYS-MATLAB co-simulation testbed. Their performance, regarding system control performance, network energy consumption and network stability, are compared to validate the proposed optimal design method. Based on the experiences and results of the test case, conclusions can be summarized as follows.

The proposed optimal design method can find an optimal topology of the WSN, on which a fully distributed optimal control approach is implemented, with very satisfactory performance including system control performance, network energy consumption and network stability. Compared with the fully connected topology, by adopting which the system control performance was the best, the optimal topology provided almost the same system control performance (i.e. both the average CO_2 were 782 ppm, the maximum CO_2 were 1,028 and 1,027 ppm, both the CO_2 unmet hour were 1.82 hours and the daily energy use of the DOAS were 122.53 and 122.50 kWh) but much lower network energy consumption. Compared with the ring-connected topology, by adopting which the network energy consumption was very low, the optimal topology had much better system control performance but a little higher network energy consumption (i.e. increased from 1,686.06 to 2,564.12 J/Day). Compared with the unstable topology, the optimal topology provided much better system control performance, a little higher network energy consumption and much enhanced network stability (i.e. extended from 36.66 to 53.90 days).

Moreover, the following issue can be investigated in the follow-up studies. As explained in the subsection 2.4, it works well with an assumption that the remaining battery capacity of the sensors is similar. However, the proposed method may not suitable for cases when different remaining battery capacity of the sensors is more common. One possible solution is modifying the sub-objective function regarding network stability, for example, as the standard deviation of the remaining battery capacity.

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