Wireless Cyber-Physical System for Building Temperature Control

CS637A: Embedded and Cyber Physical Systems
Project Presentation

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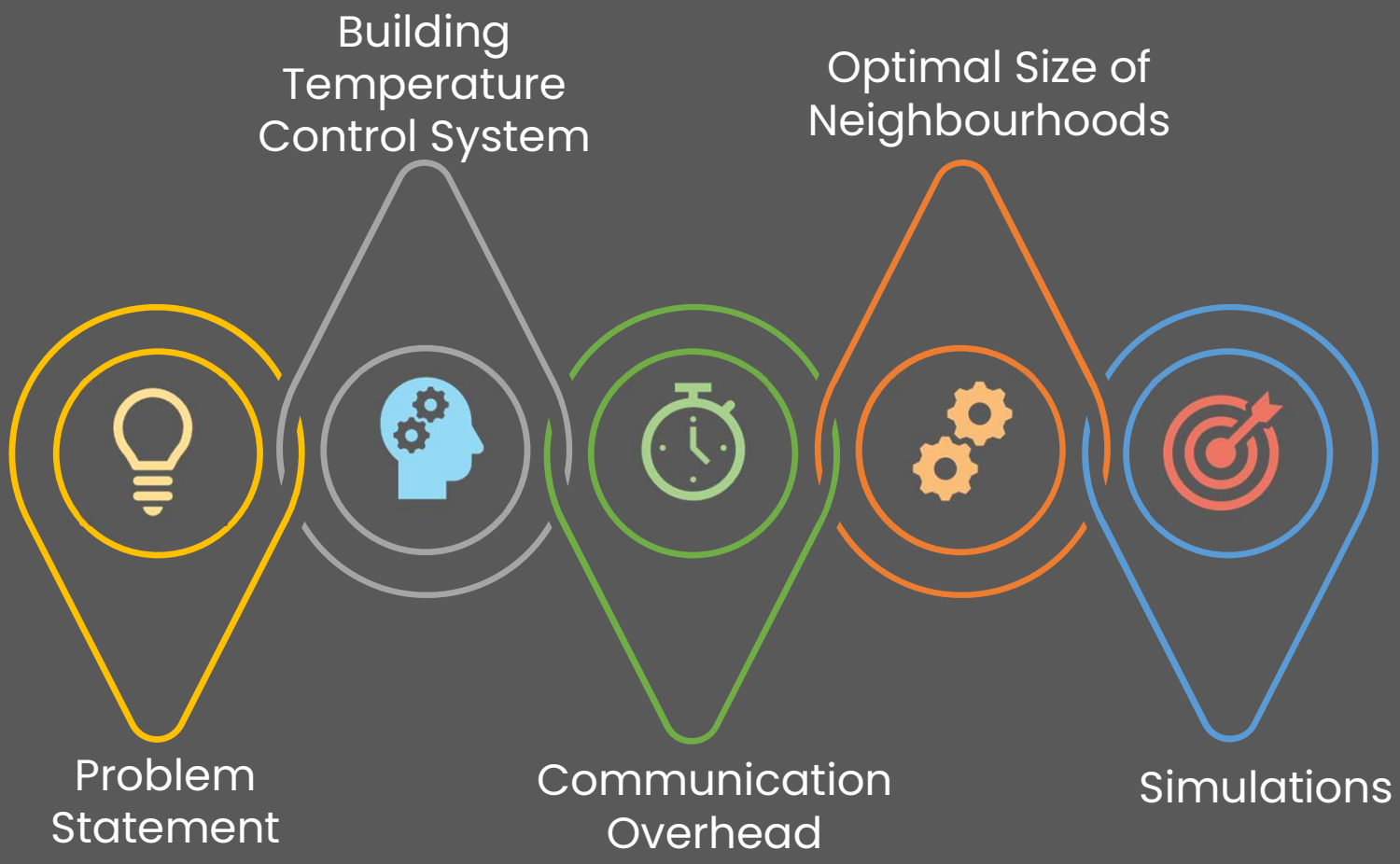
Journal:European Journal of Control 61 (2021)

Motivation and Background

- Traditional systems often use wired communication, but in this project, we have explored the benefits of large-scale wireless systems, which are easier to set up and cost-effective.
- The evolution of communication and sensor technologies has given rise to cyber-physical systems, specifically Industrial Internet of Things (IIoT) systems.
- These systems have three layers: field, communication, and computation. In the context of building control, these layers involve sensors and actuators, wireless communication modules, and remote servers for data processing.
- In this project we have discussed two methodologies for optimal control: centralized and distributed optimization.
- Wireless cyber-physical systems often face communication delays, prompting the introduction of a two-level communication architecture to manage communication overhead. The distributed optimization method used in this project efficiently balances communication within and between decision-makers.

Outline


Building Temperature Control System
Optimal Size of Neighbourhoods
Problem Statement
Communication Overhead
Simulations

Problem Statement

Developing a cyber-physical system for building automation and control, specifically for temperature regulation in an office building.

Terms used

t	Time (s)
T_i	The temperature of node i (K)
Q	Thermal energy (J)
C_i	The thermal capacitance of node i ($\frac{\mathrm{J}}{\mathrm{K}}$)
R_{ij}	Thermal resistance between zone i and j ($\frac{\mathrm{k}}{\mathrm{W}}$)
h	Heat transfer coefficient ($\frac{\mathrm{W}}{\mathrm{m^2 k}}$)
A	Area (m^2)
L	Wall/roof thickness (m)
$\dot{Q}_{in}^{i}$	The source heat transfer rate to room i (W)
$\dot{m}_s{}^{i}$	The mass flow rate from the heater to room i ($\frac{\mathrm{kg}}{\mathrm{s}}$)
c_p	The specific heat capacity of air ($\frac{\mathrm{J}}{\mathrm{kg\ k}}$)
T_s^i	The supply air temperature of room i (k)
ρ	Density of air ($\frac{\mathrm{kg}}{\mathrm{m}^3}$)
$\dot{V}$	Volumetric flow rate ($\frac{\mathrm{m}^3}{\mathrm{s}}$)
L	Control horizon length
Q, R	Weighting matrices
N_v	The total number of building rooms
x_i	The state variable of the ith subsystem
u_i	The decision variable of the ith subsystem
v_i	Interacting variable

LQ	Linear Quadratic
X_i	The closed convex subset of $\mathbb{R}^{n_i}$
$\mathcal{G}_i$	The closed convex subset of $\mathbb{R}^{m_i}$
x_i^d	The desired value for the ith state variable
S_i	The ith subsystem
$\mathcal{N}_i$	The ith neighborhood
n_j	The number of subsystems of the jth neighborhood

m_j	The size of the jth neighborhood
m_{max}	The size of the biggest neighborhood
m^*	The optimal size of neighborhood
n^j	The number of persons in the jth room

Building Temperature Control System

This section can be divided into following subsections:

1: Thermal model of a typical building
2: Optimal Control Problem
3: Distributed optimization method

Thermal model of a typical building

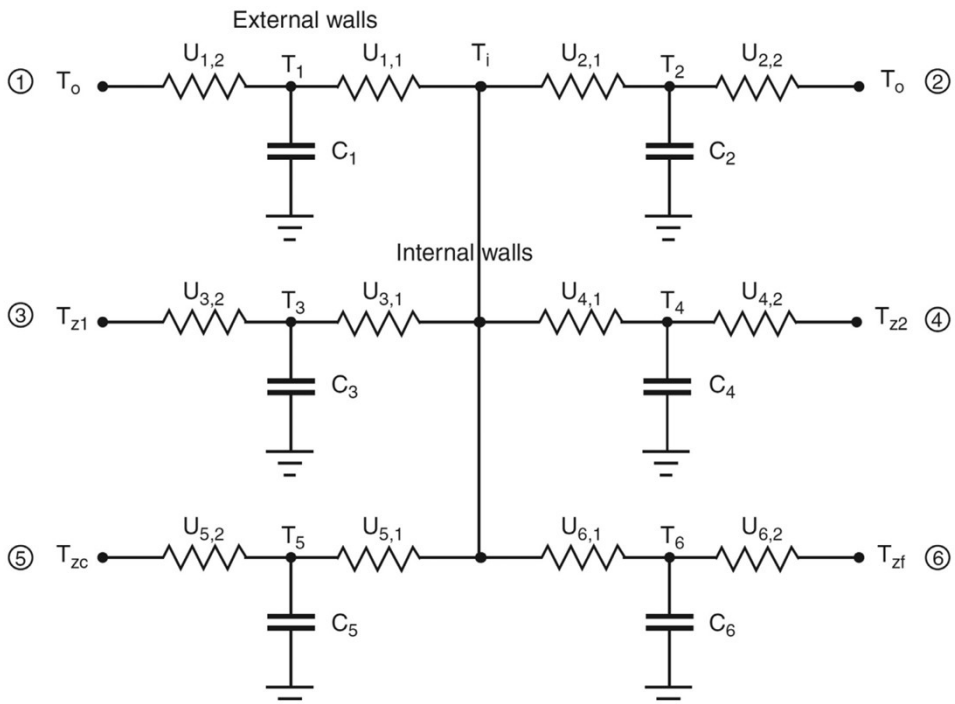
RC Model Overview

•Understanding the complexity of temperature control involves delving into the RC modeling framework for heat transfer.

•However, using complex models for large-scale systems poses its challenges. Let's explore a balance between detail and practicality.

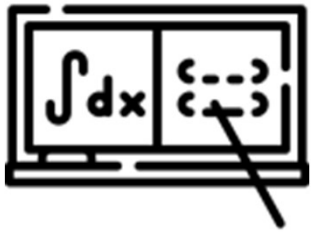
•Picture an office building as an intricate network of resistors and capacitors. Our model assumes constant pressure and balanced airflow.

•Take a look at the diagram, breaking down the components involved in heat transfer



Thermal model of a typical building

Differential Equations



- Now, let's get into the essential details of the dynamic equations (Equation (1)) that describe temperature changes in the system.

- We can draw parallels between thermal components and an electrical circuit for a clearer understanding.

$$
\begin{aligned}
C_1\dot{T}_1 &= (-U_{1,1} - U_{1,2})T_1 + U_{1,1}T_i + U_{1,2}T_o, \\
C_2\dot{T}_2 &= (-U_{2,1} - U_{2,2})T_2 + U_{2,1}T_i + U_{2,2}T_o, \\
\dot{T}_{3,4} &= -\beta_1 T_{3,4} + \frac{U_{3,2}}{C_3}U_{3,1}T_{z1} + \frac{U_{4,2}}{C_4}U_{4,1}T_{z2} + \left(\frac{U_{3,1}^2}{C_3} + \frac{U_{4,1}^2}{C_4}\right)T_i, \\
\dot{T}_{5,6} &= -\beta_2 T_{5,6} + \frac{U_{5,2}}{C_5}U_{5,1}T_{zc} + \frac{U_{6,2}}{C_6}U_{6,1}T_{zf} + \left(\frac{U_{5,1}^2}{C_5} + \frac{U_{6,1}^2}{C_6}\right)T_i, \\
C_i\dot{T}_i &= U_{1,1}T_1 + U_{2,1}T_2 + T_{3,4} + T_{5,6} \\
&\quad + (-U_{1,1} - U_{2,1} - U_{3,1} - U_{4,1} - U_{5,1} - U_{6,1})T_i + \dot{Q}_s^i, \qquad (1)
\end{aligned}
$$

Thermal model of a typical building

Thermal Dynamics and Environmental Influences

•Understanding heat transfer is crucial. Below equation helps us calculate the rate, considering factors like the Constant Air Volume (CAV) system.

$$\dot{Q}_s^i = \rho \dot{V}_s^i c_p (T_s^i - T_i).$$

•In this model, the supply air temperature is used as a decision variable.

•Open doors impact temperature exchange between rooms. The equation helps us quantify this effect.
•Consider the factors influencing heat transfer through doors for a holistic model.

$$\dot{Q}_{OD}^i = \rho \dot{V}^i c_p (T_j - T_i),$$

•The sol-air temperature (T_{sa}) is our key to considering external factors like solar radiation and convective heat transfer.

•Sol-air temperature, in contrast to outdoor temperature, gives us a more comprehensive picture.

$$T_{sa} = T_o + \frac{\alpha S}{h_o} - \frac{\xi \Delta R}{h_o},$$

Thermal model of a typical building

Simulation of a Typical Office Building

•Now, let's apply these concepts to a real-world scenario. Design Builder Software helps us simulate a four-floor office building (Figs. 2-5).
•The thermal parameters derived from this design form the basis of our model.

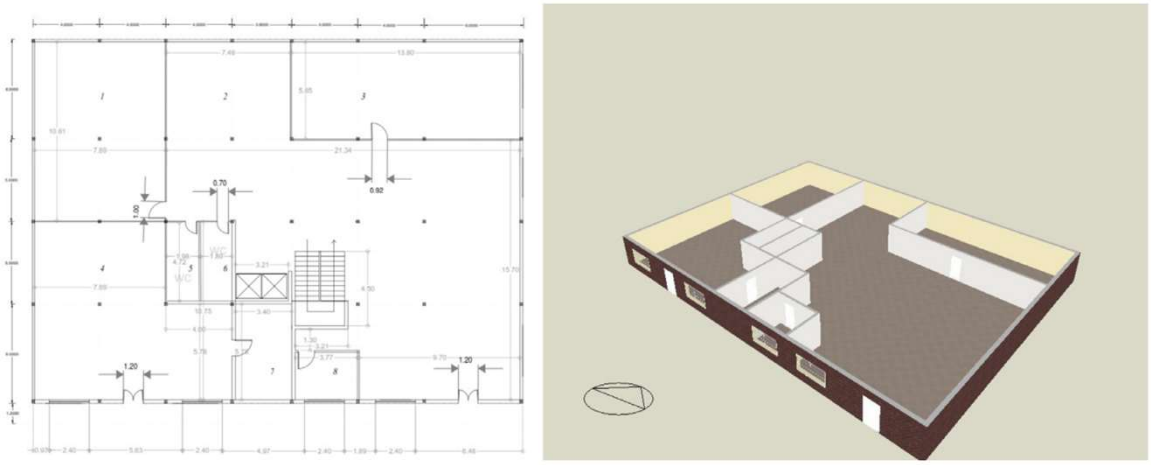


Fig. 2. Ground floor map of the office building.

Thermal model of a typical building

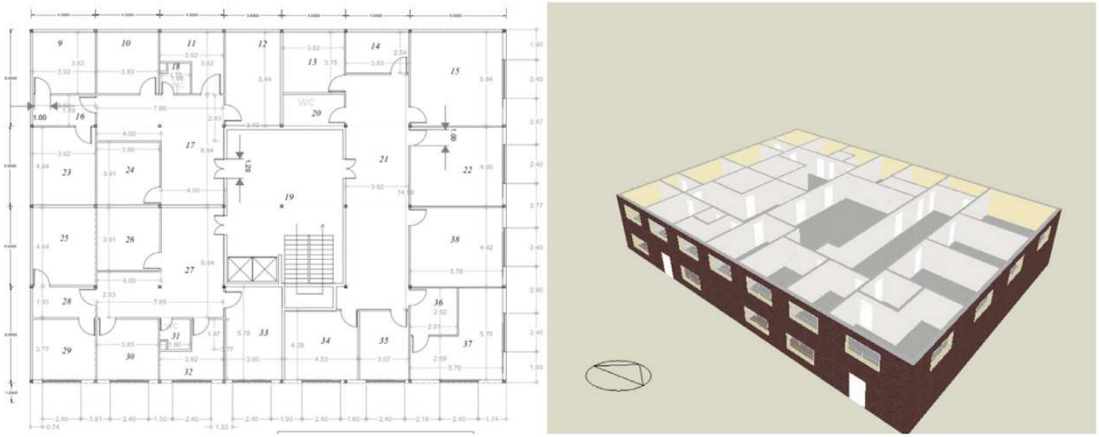


Fig. 3. First floor map of the office building.

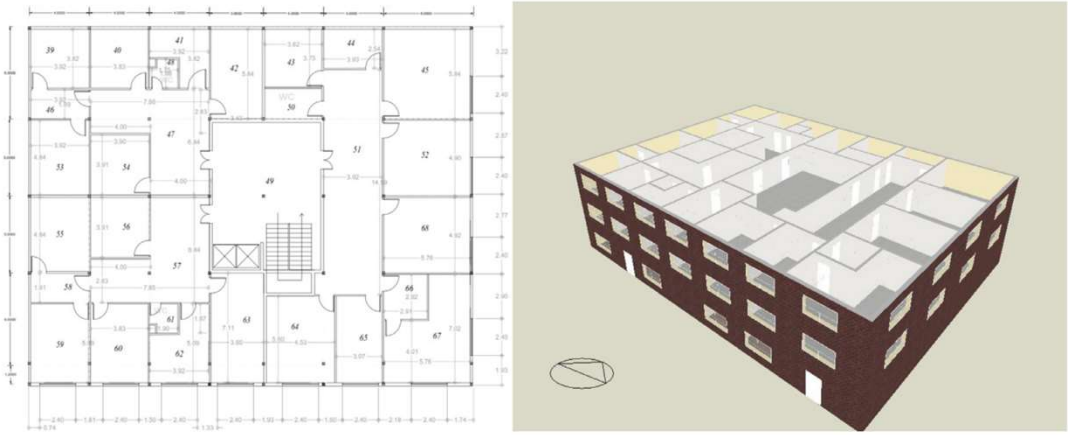


Fig. 4. Second floor map of the office building.

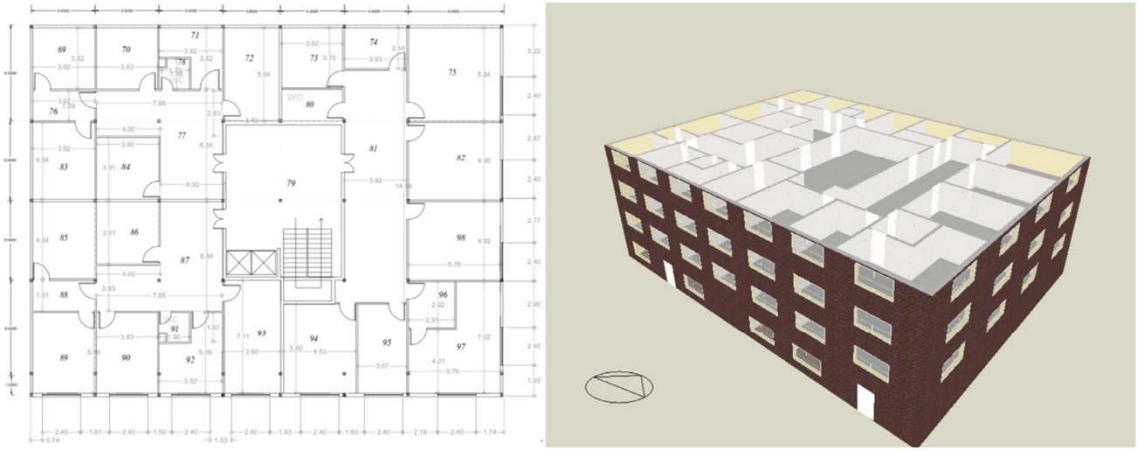


Fig. 5. Third floor map of the office building.

Thermal model of a typical building

Model Reduction

•The state space representation of this building has the following form-

$$\dot{x} = Ax + Bu,$$
$$y = Cx,$$

•Balancing detail and practicality, we employ the balanced realization theory for model reduction (Equations 10-14).

•This reduction preserves essential input-output relations crucial for our control strategy.

$$y[k] = \bar{C}_1 \bar{x}_1[k]. \tag{13}$$

$$\begin{aligned} \bar{x}_1[k+1] &= (\bar{A}_{11} - \bar{A}_{12}\bar{A}_{22}^{-1}\bar{A}_{21})\bar{x}_1[k] + (\bar{B}_1 - \bar{A}_{12}\bar{A}_{22}^{-1}\bar{B}_2)u[k] \\ &= \hat{A}\bar{x}_1[k] + \hat{B}u[k], \\ y[k] &= (\bar{C}_1 - \bar{C}_2\bar{A}_{22}^{-1}\bar{A}_{21})\bar{x}_1[k] \\ &= \hat{C}\bar{x}_1[k] \end{aligned} \tag{14}$$

$$\bar{x} = T_b x, \tag{10}$$

such that

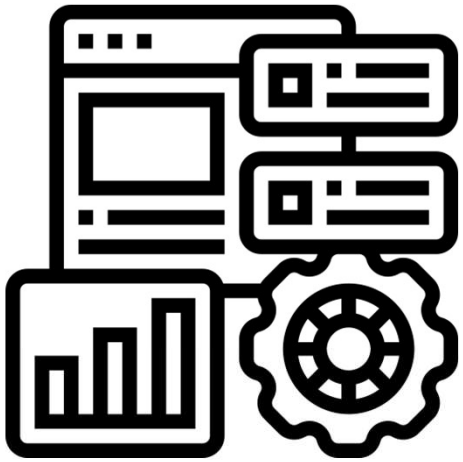
$$\begin{aligned} \bar{x}[k+1] &= T_b A T_b^{-1}\bar{x}[k] + T_b B u[k] \\ &= \bar{A}\bar{x}[k] + \bar{B}u[k], \\ y[k] &= C T_b^{-1}\bar{x}[k] = \bar{C}\bar{x}[k], \end{aligned} \tag{11}$$

$$\bar{W}_c = T_b W_c T_b',$$
$$\bar{W}_o = (T_b^{-1})' W_o T_b^{-1},$$

$$\bar{W}_c = \bar{W}_o = \Sigma = diag(\sigma_1, \sigma_2, ..., \sigma_n), \tag{12}$$
$$\sigma_1 \geq \sigma_2 \geq ... \geq \sigma_n \geq 0,$$

Thermal model of a typical building

System Dynamics



- To adapt our model for real-world scenarios, we discretize the system dynamics (Equations 15) and consider computational latency.
- The chosen time step ensures our control actions align with the system's dynamics.

$$\bar{x}_1[k+1] = \hat{A}^T \bar{x}_1[k] + \left(\sum_{j=0}^{T-1} \hat{A}^{T-j-1} \hat{B} \right) u[k]$$

$$y[k] = \hat{C}\bar{x}_1[k] \quad y[k] = y(kT), \quad \bar{x}_1[k] = \bar{x}_1[kT]. \tag{15}$$

Thermal model of a typical building

Control System

•Our control system design (Equations 16-21) comes into play. We introduce a continuous-time system and discretize it to consider computational latency.

•Control actions are applied as soon as sensor measurements are available, considering the real-world delay.

$$\dot{x}(t) = Ax(t) + Bu(t),$$

$$x(t) = e^{At}x(0) + e^{At}\int_0^t e^{-A\gamma}Bu(\gamma)d\gamma,$$

$$x[k] = x(kT) = e^{AkT}x[0] + e^{AkT}\int_0^{kT} e^{-A\gamma}Bu(\gamma)d\gamma. \tag{16}$$

$$\begin{aligned} x[k+1] &= x((k+1)T) \\ &= e^{A(k+1)T}x[0] + e^{A(k+1)T}\int_0^{(k+1)T} e^{-A\gamma}Bu(\gamma)d\gamma, \end{aligned} \tag{17}$$

$$x[k+1] - e^{AT}x[k] = e^{A(k+1)T}\int_{kT}^{(k+1)T} e^{-A\gamma}Bu(\gamma)d\gamma, \tag{18}$$

Now, if the computational latency is T_d, then

$$\begin{aligned} x[k+1] = e^{AT}x[k] &+ e^{A(k+1)T}\int_{kT}^{(kT+T_d)} e^{-A\gamma}Bu_O d\gamma \\ &+ e^{A(k+1)T}\int_{(kT+T_d)}^{(k+1)T} e^{-A\gamma}Bu_N d\gamma, \end{aligned} \tag{19}$$

where

$$u(\gamma) = \begin{cases} u_O(\text{the previous control input}), & kT \le \gamma < kT + T_d \\ u_N(\text{the new control input}), & kT + T_d \le \gamma < (k+1)T \end{cases} \tag{20}$$

$\Longrightarrow$

$$\begin{aligned} x[k+1] = e^{AT}x[k] &+ Bu_O e^{A(k+1)T}\int_{kT}^{(kT+T_d)} e^{-A\gamma}d\gamma \\ &+ Bu_N e^{A(k+1)T}\int_{(kT+T_d)}^{(k+1)T} e^{-A\gamma}d\gamma. \end{aligned} \tag{21}$$

Optimal Control Problem

Formulating The Problem Statement

•We're delving into the temperature control of a typical office building.

•Our goal is to optimize energy use while maintaining zone temperatures around desired values.

$$\min_{(u_1,u_2,\ldots,u_{N_v})} \sum_{i=1}^{N_r} \sum_{k=0}^{L-1} ||y_i[k] - y_i^d||_Q^2 + ||u_i[k]||_R^2 \tag{22}$$

$$u_{i,min} \leq u_i[k] \leq u_{i,max}, y_{i,min} \leq y_i[k] \leq y_{i,max}. \tag{23}$$

•The optimal control problem is set up with a focus on thermal dynamics and comfort constraints (Equations 22-23).

•Parameters include desired temperatures (y^d), control horizon length (L), and weighting matrices (Q and R).

Optimal Control Problem

Quadratic Cost Function

•The objective is to minimize the quadratic cost function(J_k) (Equation 24).

$$J_k = \sum_{i=1}^{N_v} \sum_{i=k}^{k+N-1} ||y_i[j] - y_i^d||_Q^2 + ||u_i[j]||_R^2, \quad N << L. \tag{24}$$

•It considers the deviation of zone temperatures from desired values and control input magnitudes.

•Operational constraints include minimum and maximum values for control inputs (u_i) and zone temperatures (y_i) (Equation 23).

Optimal Control Problem

Optimization in Action: Real-Time Control Strategies

- The cost function J_k guides the real-time solution, minimizing the quadratic cost over a shorter window ($N << L$) (Equation 24).

- This approach generates optimal trajectories for inputs and states, ensuring adherence to building dynamics and constraints.

- The first elements of the trajectory are applied to the system, and the process repeats for subsequent time steps.

- In the realm of building temperature control, this method means formulating heating/cooling plans for the next several hours to days.

- These plans are based on predictions of upcoming conditions, balancing energy efficiency and comfort.

- Summing up, our optimal control strategy enables efficient temperature regulation in office buildings.

Distributed optimization method

Challenge of Scale

•Now we're delving into the realm of distributed optimization methods, particularly crucial in large-scale building automation and control systems.

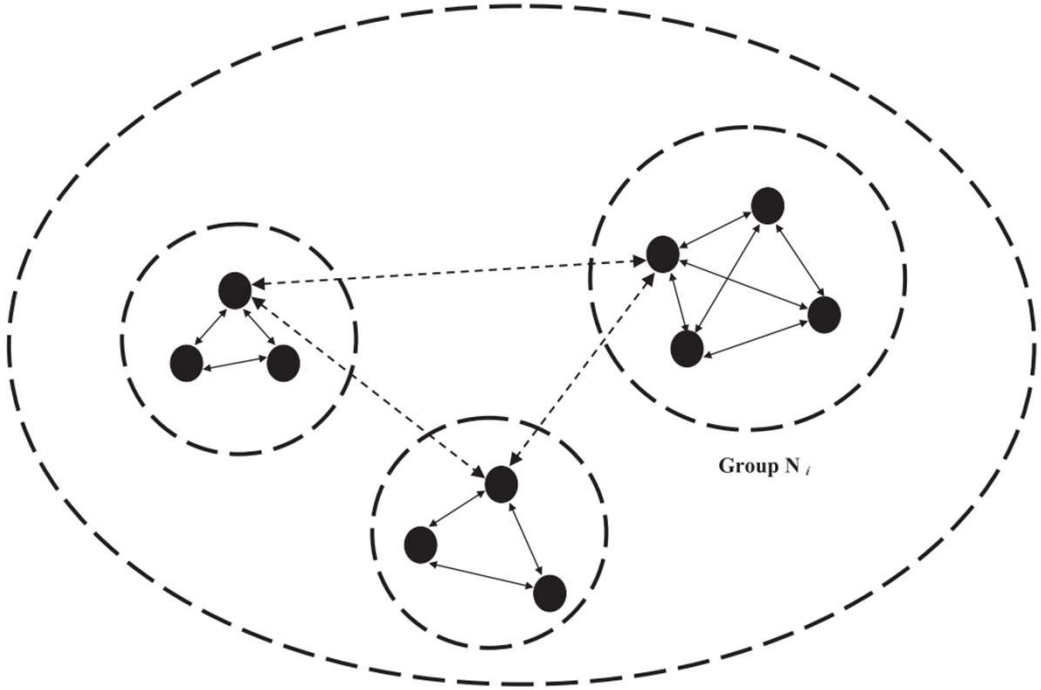
•In extensive building systems, the sheer number of constraints and decision variables poses a challenge. The computation overhead using centralized methods may not be practical within a reasonable time frame.

Distributed optimization method

Addressing the challenge

•To address scalability, a distributed optimization method is employed, utilizing a two-level hierarchical architecture for communication. See Fig for an illustration of this architecture.

•Two-level architecture for exchanging information between distributed decision-makers. Solid circle represent distributed decision-makers, solid arrows between distributed decision-makers mean frequent update and communication and dashed arrows between neighborhoods mean less frequent update and communication.



Distributed optimization method

System Description

•A three-step algorithm, as introduced in [44], overcomes computation scalability issues. However, the feasibility, convergence, and optimality were not initially proven, but this gap was filled in [19].

•Each subsystem, denoted as S_i, in a system of N_v distributed interacting linear time-invariant subsystems, has its decision-maker, with a decision variable u_i. The subsystem dynamics are described by equations (25).

$$S_i : x_i[k+1] = A_i x_i[k] + B_i u_i[k] + v_i[k], \quad y_i[k] = C_i x_i[k], \\ i = 1, 2, \ldots, N_v, \quad k \in \{0, 1, 2, \ldots, N-1\}, \tag{25}$$

where x_i, u_i and y_i are the state variable, the decision variable and the output of the ith subsystem, respectively, and v_i is the interacting variable that summarizes the effect of other subsystems on subsystem with the decision-maker S_i:

$$v_i[k] = \sum_{j=1, j \neq i}^{N_v} (M_{ij} x_j[k] + N_{ij} u_j[k]). \tag{26}$$

[44] B.T. Stewart, J.B. Rawlings, S.J. Wright, Hierarchical cooperative distributed model predictive control, in: American Control Conference (ACC), 2010, IEEE, 2010, pp. 3963–3968.

[19] A. Farhadi, A. Khodabandehlou, Distributed model predictive control with hierarchical architecture for communication: Application in automated irrigation channels, International Journal of Control 89 (8) (2016) 1725–1741.

Distributed optimization method

Optimization Problem

•The Linear-Quadratic (LQ) constrained optimization problem (Equations 27-28) is formulated for each subsystem, subject to system dynamics and operational constraints.

•Notably, the optimization problem mirrors that of building temperature control discussed earlier. The challenge here is the computational feasibility for large-scale systems.

•The distributed method of [19] is employed. It involves initialization, inner iterate updates, and outer iterate updates, ensuring information exchange between subsystems and neighborhoods.

$$\min_{u}\{J_k(x[k], u_1, \ldots, u_{N_v}), \text{subject to } (25)\ x_i[j] \in X_i, u_i[j] \in \mathcal{G}_i, \quad \forall i, j \in \{k, k+1, \ldots, k+N-1\}\}, \tag{27}$$

$$J_k(x[k], u_1, \ldots, u_{N_v}) \doteq \sum_{i=1}^{N_v} \sum_{j=k}^{k+N-1} \|x_i[j] - x_i^d\|_Q^2 + \|u_i[j]\|_R^2 \tag{28}$$

Distributed optimization method

Conclusion

•The method's feasibility, convergence, and optimality are proven. As time progresses (denoted by T), the approximated solution (u_{T1}^*, u_{T2}^*, ..., u_{Nv}^*) converges to the optimal solution.

•We define communication overhead, computation overhead, and computational latency, critical metrics in assessing the efficiency of the three-step algorithm.

•Summing up, distributed optimization methods provide a scalable solution for large-scale building systems. The proven feasibility and convergence make them a valuable tool in overcoming computational challenges.

Computational Latency

- Communication overhead is the total time spent exchanging information between distributed decision-makers to approximate the solution of an optimization problem.
- Communication overhead consists of communication, computation, and computational latency.
- Computation overhead involves the processing time of dominated neighborhoods in the optimization problem. At a given outer iteration, the neighborhood with the longest processing time for inner iterations is defined as the dominating neighborhood at this iteration.
- Computational latency is the sum of communication and computation overhead.

IEEE 802.15.4/ZigBee communication technology

This paper focuses on IEEE 802.15.4/ZigBee communication technology for communication purposes. IEEE 802.15.4 standard and other specifications of ZigBee illustrate outstanding communication technologies for large-scale, low data rate, low cost, low power consumption, and simple operation wireless networks

The Standard supports two medium access modes that can be selected by the Personal Area Network (PAN) Coordinator:

1. The non-beacon-enabled mode
2. The beacon-enabled mode.

Non-Beacon-Enabled Mode:

- Utilizes unslotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) channel access protocol
- Collision avoidance based on random delays
- Cannot ensure collision-free and predictable access
- Lacks time and resource guarantees

Beacon-Enabled Mode:

- Coordinator sends periodic beacon frames
- Synchronizes nodes and recognizes the PAN
- Offers contention-free Guaranteed Time Slot (GTS) mechanism
- Supports time-critical data transmissions
- Provides collision-free and predictable access to the wireless medium

Topologies and Types of Devices

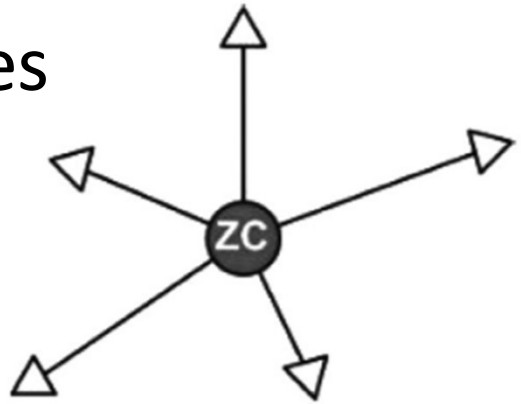
- Three types of devices are defined in ZigBee specification: ZigBee Coordinator (ZC), ZigBee Router (ZR), and ZigBee End Device (ZED).

1) ZC initiates and configures ZigBee network formation.

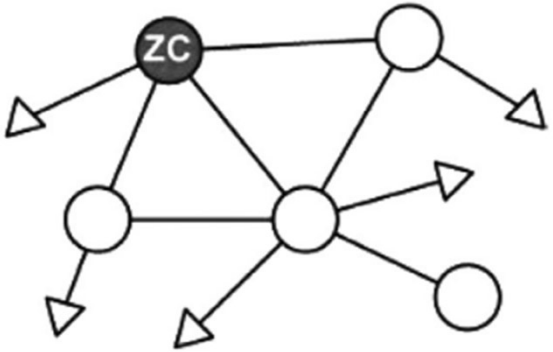
2) ZR is associated with a ZC or a formerly associated ZR and takes part in multi-hop routing of messages within the ZigBee network.

3) ZED primarily focuses on end-device functions, not involved in network coordination or routing.

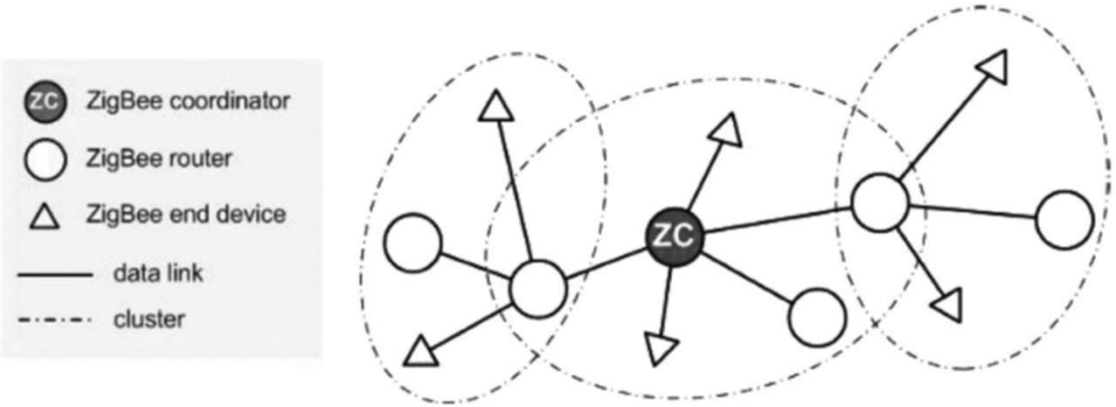
- Supports star, mesh, and cluster-tree topologies.



Star Topology

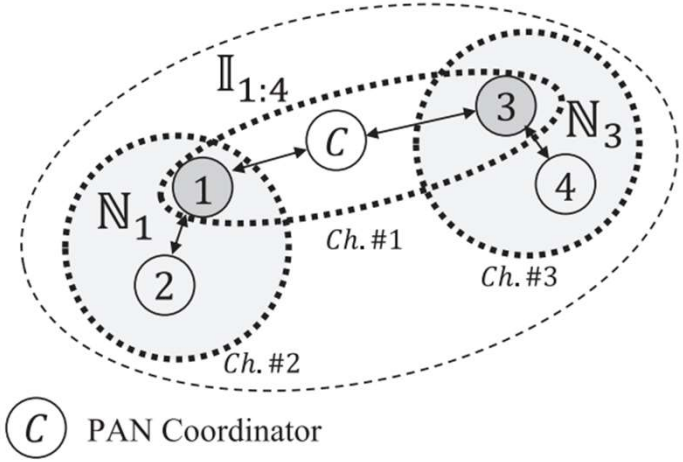


Mesh Topology



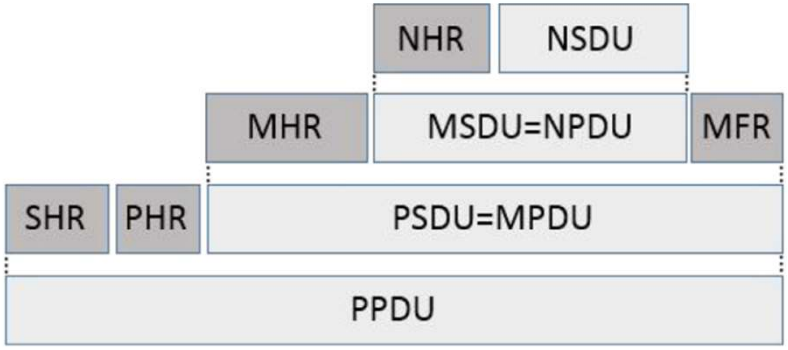
Cluster-Tree Topology

Communication Architecture using ZigBee Modules



Two-level architecture for exchanging information between distributed decision-makers using ZigBee modules

- two-level architecture for exchanging data between decision-makers.
- frame structure of IEEE 802.15.4/ZigBee frames.



Structure of IEEE 802.15.4/ZigBee frames

Inner vs Outer Iterate

Inner Iterate:

- Involves communication between nodes and their respective cluster heads. It focuses on exchanging information data, optimizing GTS allocation, and ensuring efficient communication within a local cluster.

- Local communication within clusters.

Outer Iterate:

- Extends the communication to a higher level, involving interactions between cluster heads and the central coordinator (PAN coordinator). This outer iterate coordination ensures synchronization and effective communication across the entire network.

- Expands communication to the network's central coordination.

Communication Time Calculations

- Calculation of frame transfer times for beacon frames, data frames, acknowledgment frames, and command frames.
- Specifies the parameters used in the calculations, such as Beacon Order (BO) and Super frame Order (SO).

Beacon Frame Transfer Time (B):

$$\mathcal{B} = \frac{(6+11+23+14+22)\times 8}{250\times 10^3} = 2.432 \text{ ms.}$$

Data Frame Transfer Time (D):

$$\mathcal{D} = \frac{(6+9+16)\times 8}{250\times 10^3} = 1.120 \text{ ms.}$$

Acknowledgment Frame Transfer Time (ACK):

$$\text{ACK} = \frac{(6+5)\times 8}{250\times 10^3} = 0.352 \text{ ms.}$$

Command Frame Transfer Time (C):

$$\mathcal{C} = \frac{(6+10+17)\times 8}{250\times 10^3} = 1.056 \text{ ms.}$$

Communication Overhead Calculations

- Derives the formula for communication overhead (C_{com}) as a function of inner and outer iterate communications.
- Takes into account the number of super frames required in inner and outer iterates, as well as the size of the largest cluster.

Communication Overhead Calculation (Ccom):

$$Ccom = Cincom + Coutcom$$

a. **Inner Iterate Communication (Cincom):**

$$Cincom = B + (m_{\max} - 1)(C + a\text{TurnaroundTime} + A + \text{LIFS}) + (m_{\max} - 1)(m_{\max})(D + L_0 + \text{LIFS}) + 2n_{\text{si}} \times a\text{MinCAPLength}$$

b. **Outer Iterate Communication (Coutcom):**

$$Coutcom = B + q(C + a\text{TurnaroundTime} + A + \text{LIFS}) + q\left(\sum_{j=1}^{q}(D + m_j \times L_0 + \text{LIFS})\right) + 2n_{\text{so}} \times a\text{MinCAPLength}$$

Where:

- n_{si} and n_{so} are the numbers of superframes required in inner and outer iterates, respectively.
- $m_{\max}$ is the size of the largest cluster.
- q is the total number of outer iterates.

Optimal Size of Neighbourhoods

- For the typical office buildings(shown in the next slide),we find the size of the neighbourhoods having the lowest computational latency.
- Assumptions:

1.All neighbourhoods are of the same size(mj=m for all j)

2.For a given m,each neighbourhood involves nearby rooms/hallways from the same floor or different floors.

- Since a mathematical relation is nearly impossible, we use computer simulations to get the best neighbourhood size.
- We use the distributed optimization method covered earlier.
- An average value of m* is calculated with different initial conditions,and the best m* is chosen based on these values.

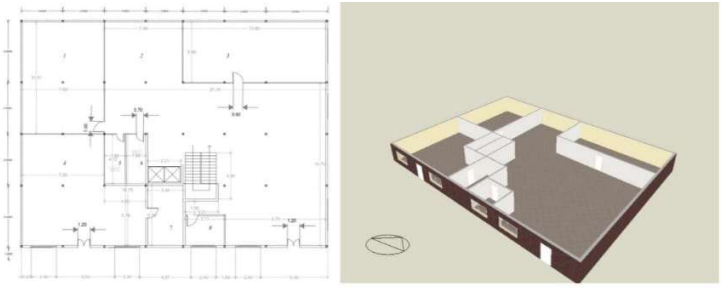


Fig. 2. Ground floor map of the office building.

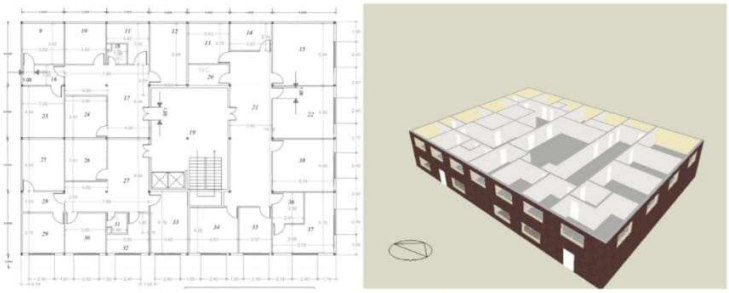
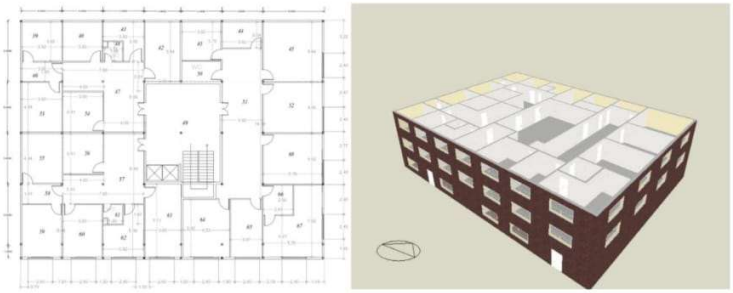


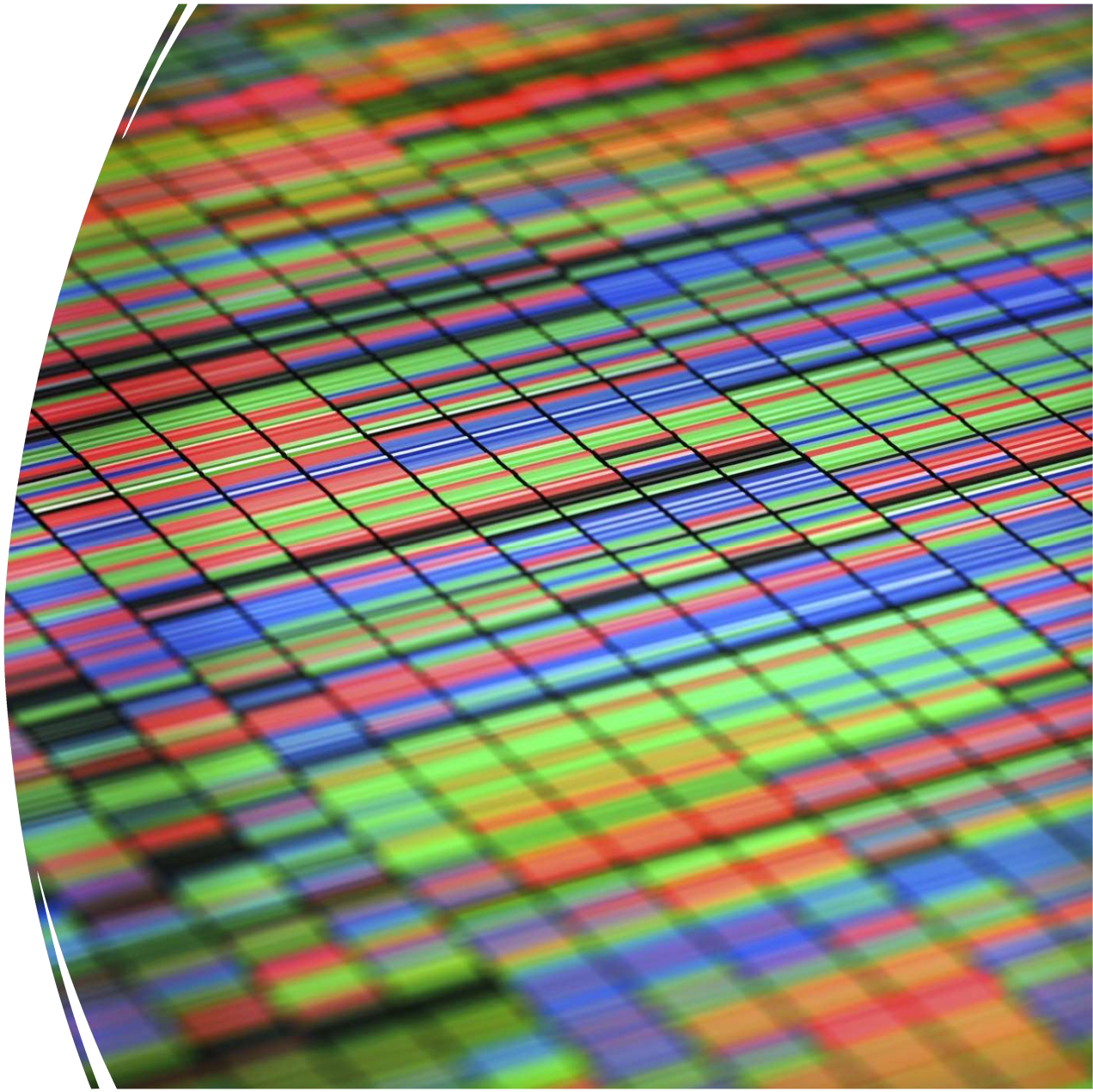
Fig. 3. First floor map of the office building.



Typical office buildings

SIMULATION PARAMETERS

- For the simulation, we set N = 6, λi = 1/q , wi = 1/m ,€ = 5, p¯ = 10, yi,d = 22 ◦C, ui,min = 15, ui,max = 40, yi,min = 10, yi,max = 25, Q = 100R, and R = I, B = 2.432 ms, D = 1.120 ms, L0 = 0.256 ms, L = 0.128 ms, A = 0.352 ms, C = 1.056 ms, aMinCAPLength = 7.04 ms, aTurnAroundTime = 0.192 ms, and LIFS = 0.64 ms.



Simulation,continued..

All the simulations are run on a laptop with Windows 64-bit operating system, 1.73 GHz core i7 processor, and 8 GB RAM memory. In real applications, the embedded processor of each ZigBee module can be used for performing the required computation. As each node only needs to perform a very simple computation, the communication overhead is the dominating factor in computational latency.

The initial conditions are given in the next slide.

Initial conditions for the simulation

Table 2
Different types of neighborhoods in the typical office building.

Number of neighborhoods (q)	Size of neighborhoods (m_j)	m_{max}	n_{si}	q	n_{so}
6	18, 18, 18, 18, 18, 8	18	3	6	1
7	14, 14, 14, 14, 14, 14, 14	14	2	7	1
9	11, 11, 11, 11, 11, 11, 11, 11, 10	11	2	9	2
14	7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7	7	1	14	2

Table 3
Initial conditions for different m.

Ambient temperature(T_{oa}) °C = Inside temperature($x_i[0]$) °C	Initial input (u_0^i) °C
10	30
12	30
14	30
16	30

Simulation results

- average total number of iterations for e - convergence

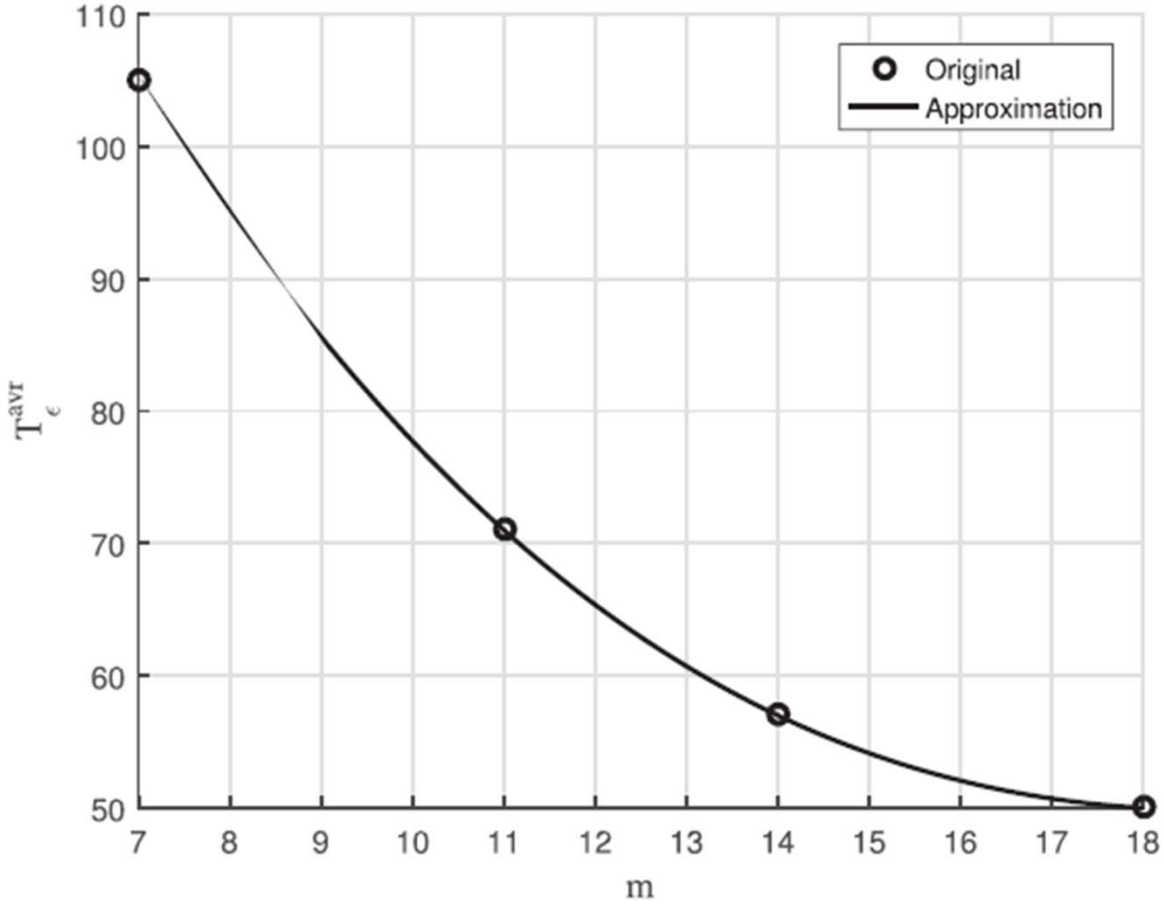


Fig. 17. Circle: average T_ϵ for m =7,11,14,18. Solid line: curve fit $T_\epsilon^{avr} = -0.0119m^3 + 0.9286m^2 - 22.2738m + 219.5$.

The average communication overhead

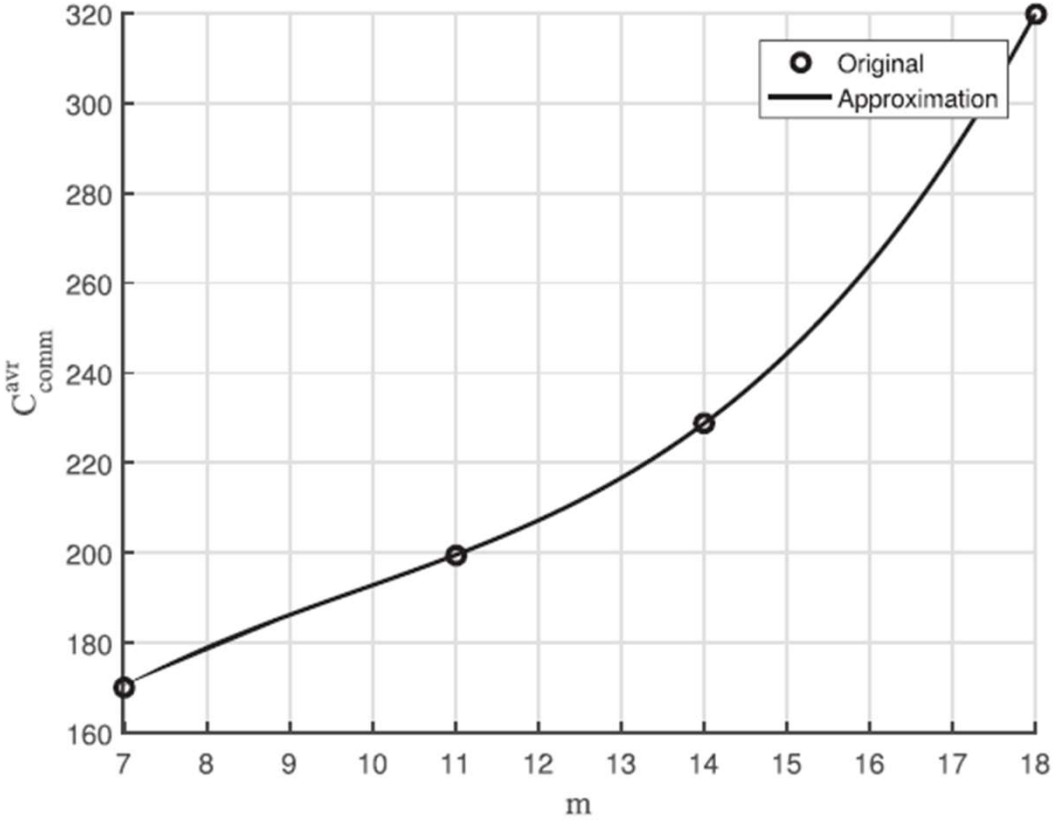


Fig. 19. Circle: average communication overhead in second for m =7,11,14,18. Solid line: curve fit $C^{avr}_{comm} = 0.1385m^3 - 4.0974m^2 + 46.8948m - 4.986$.

the average computation overhead

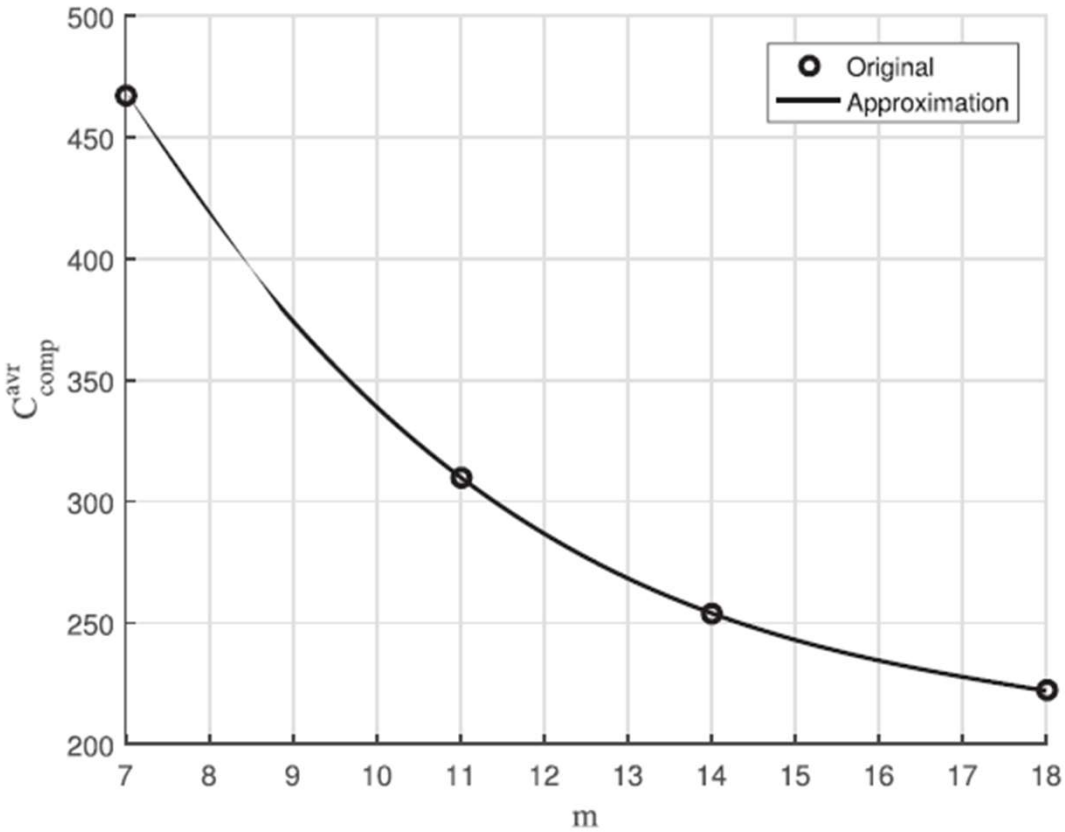


Fig. 18. Circle: average processors computation overhead in second for m =7,11,14,18. Solid line: curve fit $C^{avr}_{comp} = -0.1287m^3 + 7.0616m^2 - 134.5497m + 1107$.

The average computational latency

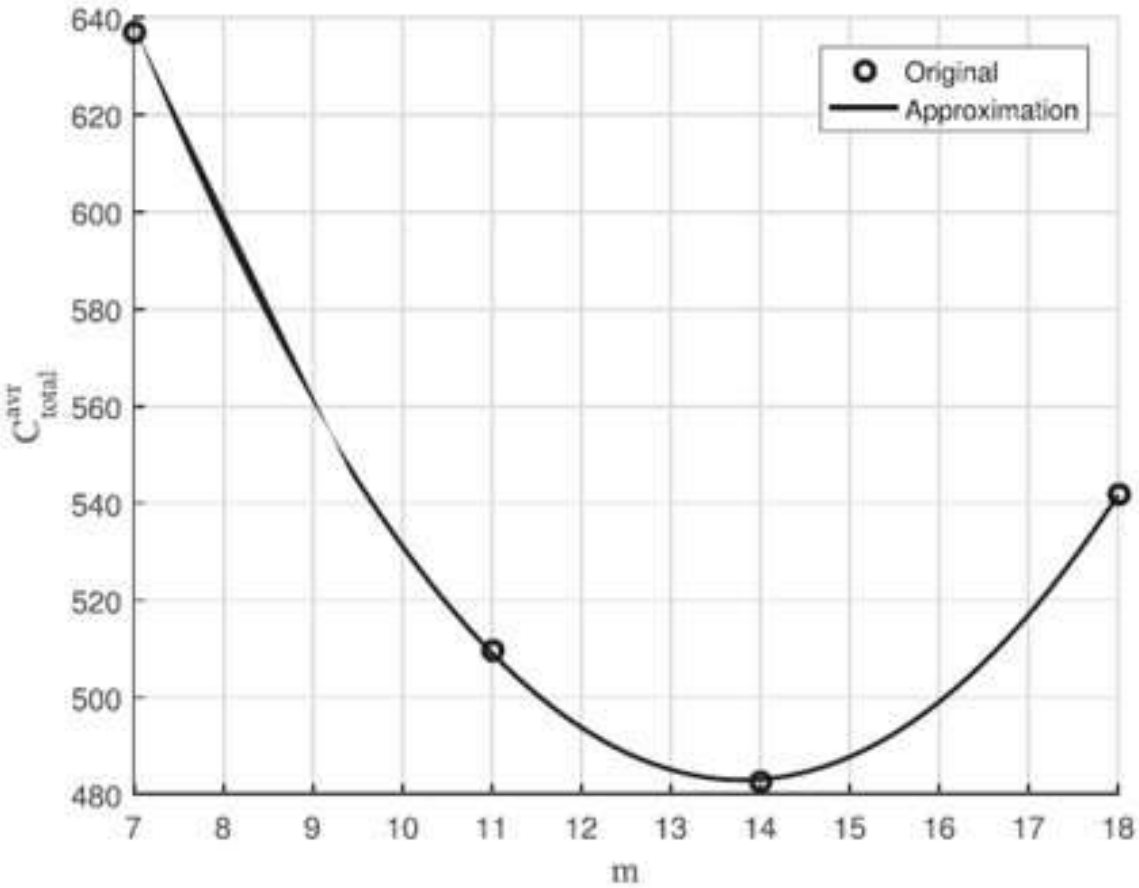
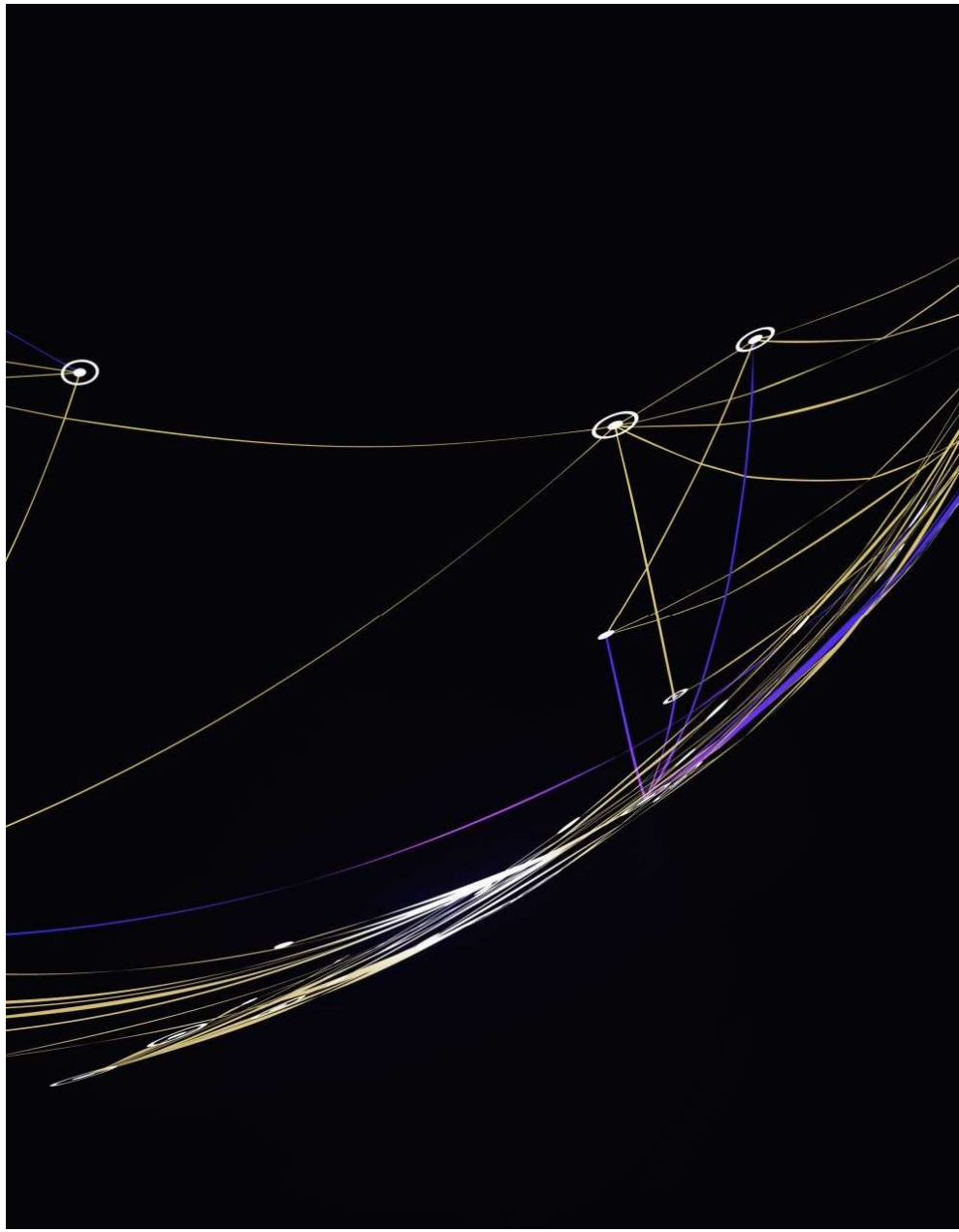


Fig. 20. Circle: average computational latency in seconds for m =7,11,14,18. Solid line: curve fit$C^{avr}_{total} = 3.33m^2 - 91.96m + 1117.6$.

Analysis

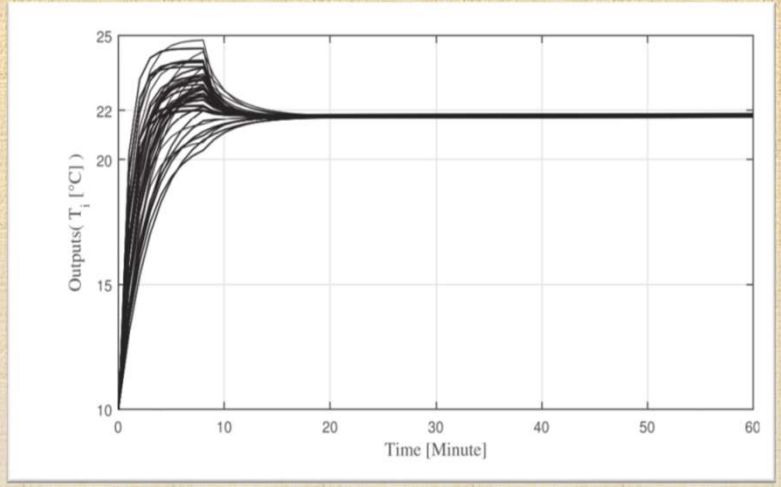
- As it is clear from the above figures, by increasing the size of neighborhoods m, the communication overhead increases and the computational overhead decreases. Therefore, as it is seen from the last graph, the computational latency, which is the summation of communication overhead and computation overhead, is approximated by a second-order polynomial, which has a minimum; and for the conditions simulated, this minimum is $m* = 14$. $m*$ corresponds to the size of neighborhoods, which are neither very small nor very large.

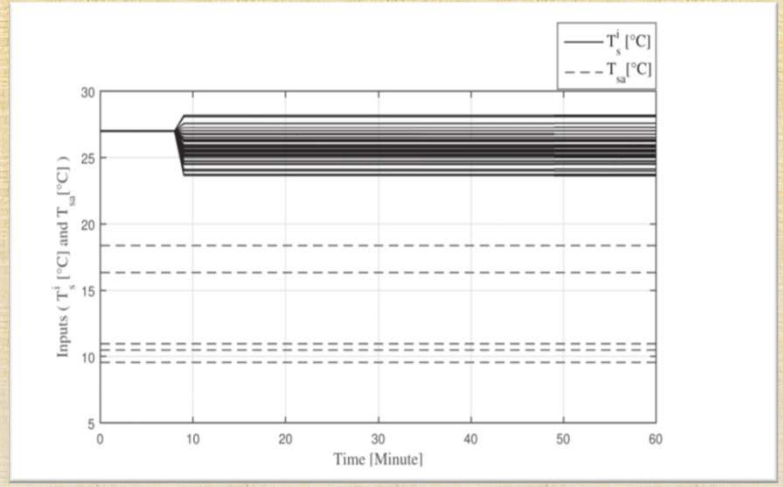


SIMULATION

RESULTS

GRAPH OF OUTPUT TEMP(T_I) AND INPUT (T_S AND T_{SA}) V/S TIME(T)

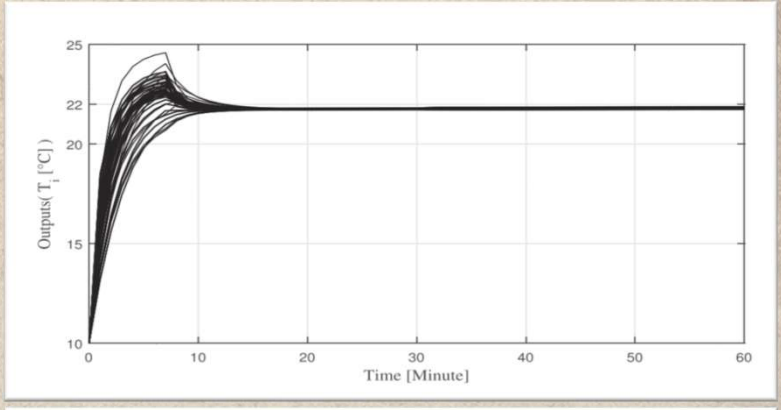


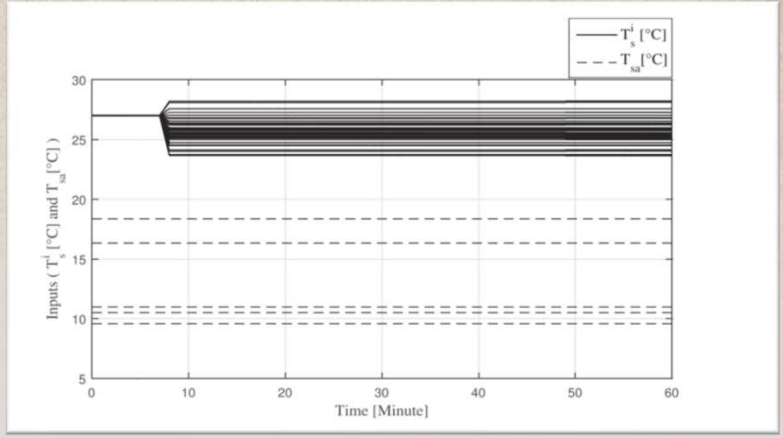


Distributed Model Predictive Control (m∗ = 14) effectively maintains temperature in an office building, with closed internal doors, revealing room and hallway temperatures as well as sol-air temperatures by orientation.

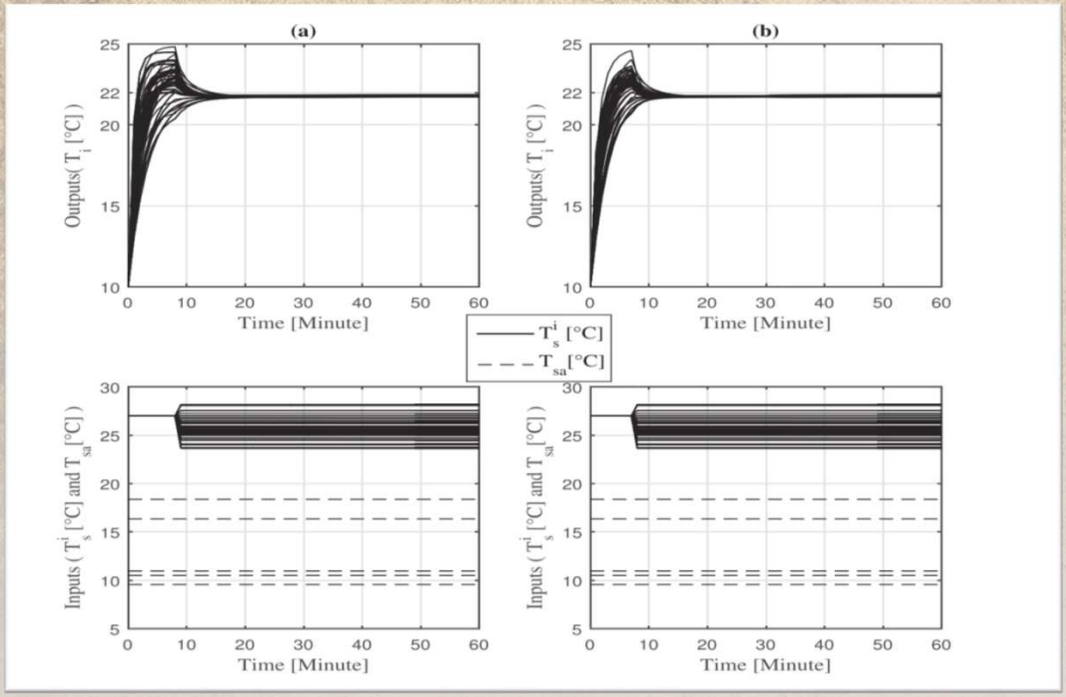
GRAPH OF OUTPUT TEMP(T_I) AND INPUT (T_S AND T_{SA}) V/S TIME(T)

In the initial 30 minutes, with open internal doors, observe the temperature dynamics and sol-air variations in each room/hallway and orientation of a typical office building. Upon applying distributed model predictive control (m∗ = 14), analyze the subsequent impact and stabilization following the closure of internal doors.





GRAPH OF OUTPUT TEMP(T_I) AND INPUT (T_S AND T_{SA}) V/S TIME(T)



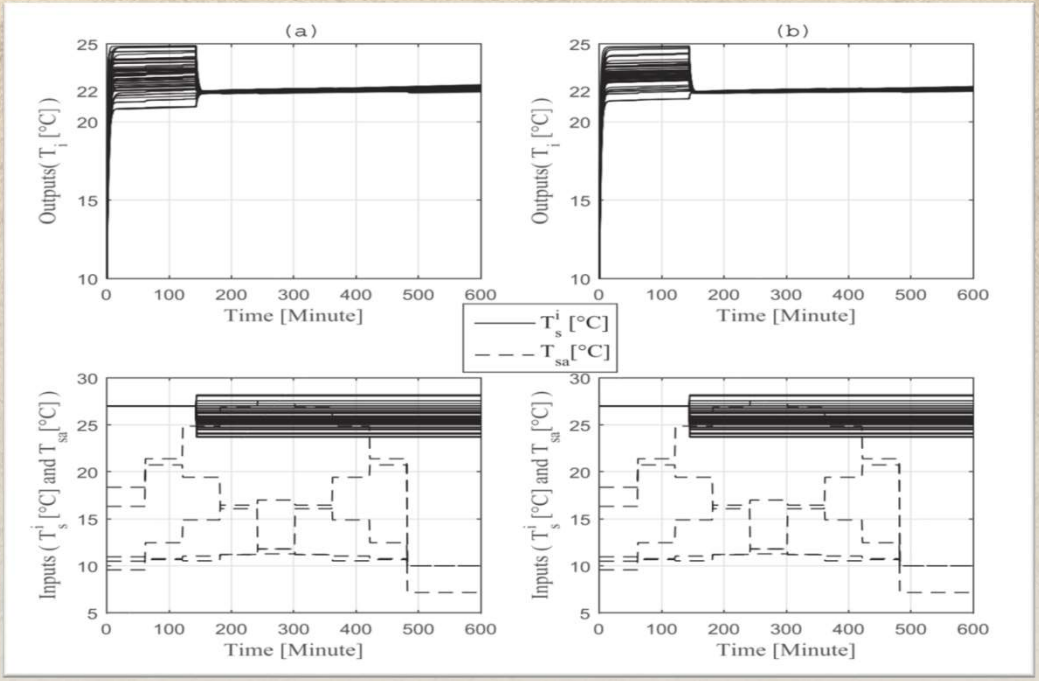
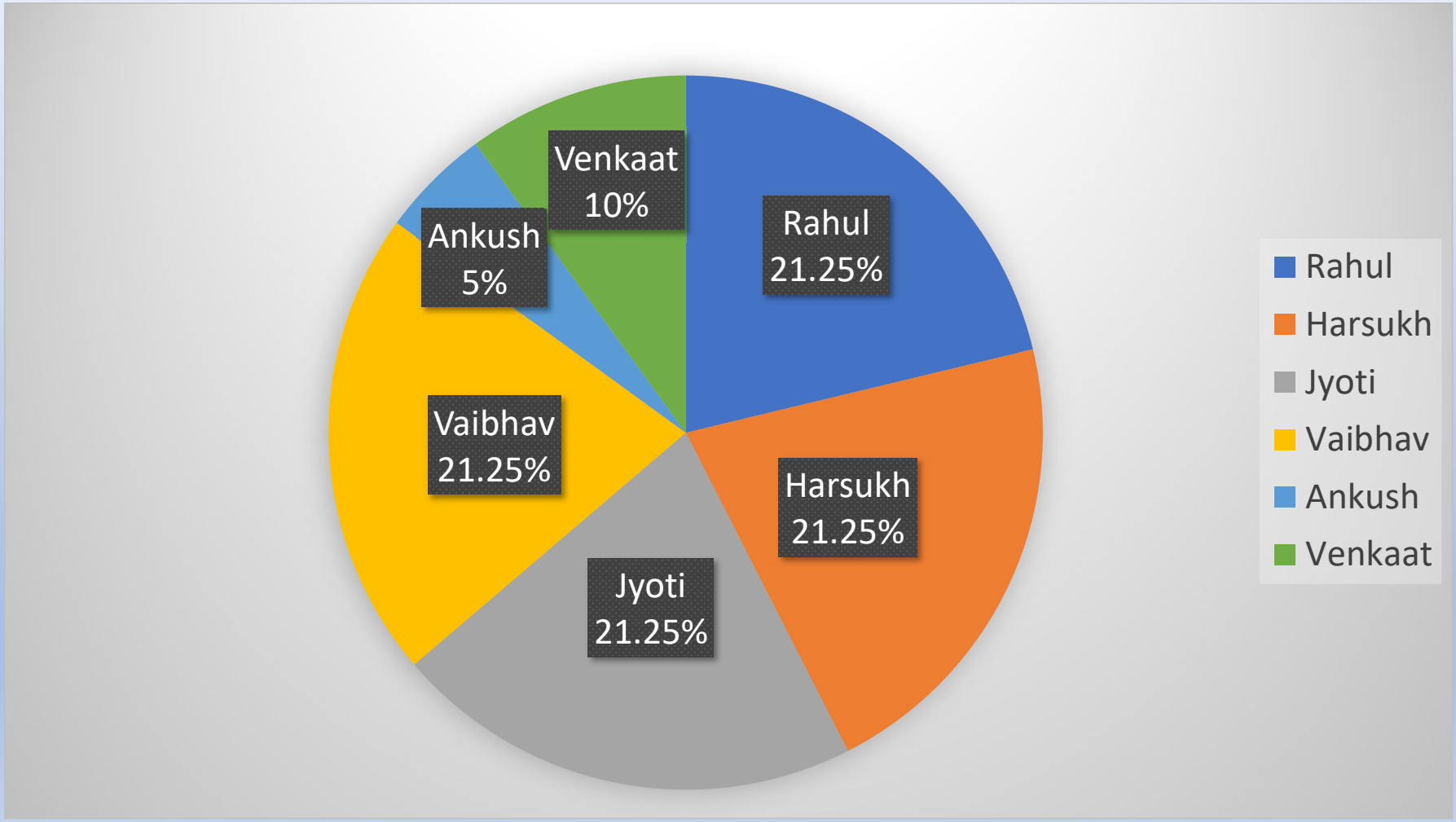
(a) Analyze temperature and supply air control within a two-level communication architecture with optimal neighborhood sizes, emphasizing the impact of closed doors throughout the simulation in a typical office building.

- (b) Investigate the dynamic thermal behavior when doors are open during the initial 30 minutes, followed by closure, within a two-level communication architecture with optimal neighborhood sizes in a typical office building.

GRAPH OF OUTPUT TEMP(T_I) AND INPUT (T_S AND T_{SA}) V/S TIME(T)

(a) Closed internal doors throughout the simulation showcase temperature control with one neighborhood and 98 subsystems in a typical office building

(b) Initial 30-minute open-door scenario followed by closure illustrates the dynamic impact on temperature and supply air temperature with one neighborhood and 98 subsystems in a typical office building



Contribution of Each Team Member