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RESEARCH ARTICLE

Intelligent Routing Protocol for Decentralized Cyber Physical System Using Smart Grid Applications

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Abstract— Sensors have been playing a crucial role in cyber physical decision making system. The performance quality of a cyber-physical system depends on the number of sensor feedback data applied to it and how it works on them. A sensor network is a network of low-powered, energy-constrained nodes equipped with sensor(s) and wireless communication devices that are intended to sense some physical phenomena from the area of deployment. Recent technological advances in the field of micro-electro mechanical systems (MEMS) have made the development of multi-functional sensor nodes technically and economically feasible. The sensor nodes in a sensor network are usually resource constrained, which means they have limited energy, limited processing and memory. Sharing all the available sensor data to all the cyber physical system is impractical due to bandwidth constraint. An intelligent router system is proposed in this system to effectively route the sensor data to the relevant high impact voltage grids, by using effective maximum link time routing path to the bandwidth constraints.

I. INTRODUCTION

In Recent years, cyber physical systems (also known as networked control systems in many scenarios), which consist of computing and physical sub-systems, have received considerable attention [15] due to their wide applications in various areas such as power grids [11], robotic networks [4] and embedded systems [23]. A typical cyber physical system has the capabilities of sensing, controlling and communication. In many cases, the sensor(s) and controller(s) are not located at the same place. Hence, a communication network is needed to convey the system observations from the sensor(s) to the controller(s). An important application of cyber physical systems is smart grid [11], in which the power grid is the physical world while the communication system for monitoring and controlling the power grid bridges the physical world and computing systems. An example in the context of voltage control in smart grid is shown in Fig. 1, where there are three sensors, three relay nodes and three distributed energy.

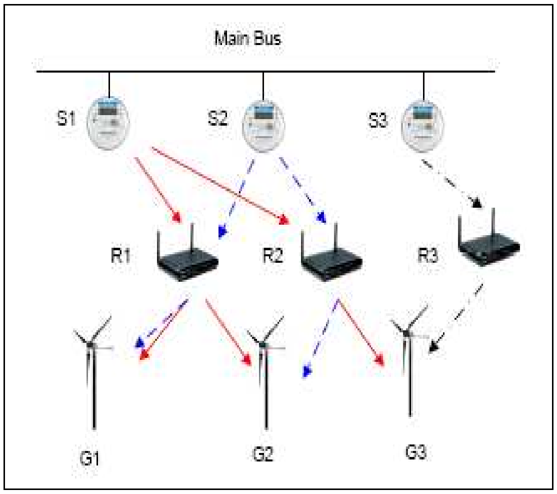


Fig. 1. An illustration of communications in cyber physical systems: a case study of smart grid. Different data flows are represented by different arrows

(DEGs) plays the role of controllers. The communication network conveys the sensor observations, i.e., the voltage measurements at the points of common coupling (PCCs) at the main transmission line, to the controllers in order to stabilize the voltage to a reference value. As in traditional data communication networks or sensor networks, routing is needed to find paths from the sensors to the controllers. In particular, an observation at a sensor may need to be sent to multiple controllers. For example, two or more DEGs may need to monitor the voltage at one point in order to take control actions (increasing or decreasing their voltages) since their control actions are coupled in the voltage dynamics. Hence, multicast routing [5] [12] [24] is needed1. In a sharp contrast to traditional communication networks, multicast routing in cyber physical systems is challenging due to the following issues:

- Uncertain destinations: In traditional networks, the destinations are known in advance; e.g., in video streaming, the destinations are the customers requesting the video clip. However, in cyber physical systems, the destinations are unknown in advance, which consists of one of the most important design parameters. If the bandwidth allows, it is desirable to broadcast the observations of each sensor to all controllers since the control actions may be coupled and a joint control may better stabilize the system. When the bandwidth is limited, it is challenging to determine the set of destinations for each sensor.

For example, in Fig. 1, DEG G3 has weak impacts on the voltages at S1 and S2 but a strong impact on the voltage at S3. Thus, if the bandwidth is sufficiently large, we can build routes from S1, S2 and S3 to G3, which can improve the performance of control; otherwise, we need to consider only the path from S3 to G3, at the cost of some performance loss.

- Multiple routing modes2: In traditional networks, usually the multicast routing process results in one set of paths, which we call a routing mode, for the sources and destinations. However, in cyber physical systems, a single routing mode may not stabilize the cyber physical system. It is possible that we choose multiple routing modes and let the communication network switch its operation among these routing modes in an adaptive manner. From the viewpoint of system theory, each routing mode corresponds to a mode of the system dynamics. According to the theory of hybrid systems [20], switching among multiple unstable system modes may result in stable dynamics. A trivial solution is to consider all possible routing modes and find the switching rules among all these routing modes; however, the set of modes will be prohibitively large for a large network. Hence, the challenge is how to find a reasonable set of routing modes for stable system dynamics.

In this paper, we study multicast routing in cyber physical systems, concentrating particularly on the above two challenges, namely the determination of destinations and routing modes. We will formulate routing as an optimization problem, by employing the theories of hybrid systems and linear matrix inequalities (LMIs), and then solve the optimization problem using heuristic approaches. Although there have been some studies on the design of communication for networked control systems [18] [19] [26]3, they are mostly focused on the physical layer and consider only centralized controls. In [8], the routing problem is studied for the purpose of system state estimation. Unlike our study, [8] considers a single and fixed destination controller; moreover, it assumes that there is only one sensor such that the conflict among multiple data flows can be ignored. In [14], the communication topology is designed for distributed control, where the communication delay is ignored. To our knowledge, this paper is the first to study networking in generic cyber physical systems with decentralized sensors and decentralized controllers4. The proposed framework shrinks the gap between the communities of communication and control and sheds light for future studies of communication system design for cyber physical systems. Based on the study of generic cyber physical systems, we will apply the proposed framework in the context of voltage control [1] [17] for DEGs in smart grid, as a case study. The proposed framework can also be applied in other controls of power grid, e.g., frequency control [27], since they are all special cases of controlling cyber physical systems. The remainder of this paper is organized as follows.

Model for cyber physical systems will be explained in Section II. The routing algorithm with ignorable delay will be discussed in Section III. Then, the study will be extended to the more generic case in which the delays are non-negligible. Numerical simulations will be carried out in the context of voltage control in smart grid in Section VI. Conclusions will be drawn in Section VII.

II. SYSTEM MODEL

In this section, we introduce the system model which contains the physical dynamics and the communication network. Certain assumptions will be made to simplify the analysis without losing the essence of the study.

A. Model of Physical Dynamics

We assume that there are Nc controllers and Ns sensors in the cyber physical system, all being decentralized. For simplicity, we assume that the control action at each controller is scalar, as is the observation at each sensor. This simplifies the mathematical notation and can be straightforwardly extended to the generic case of vector control actions or vector observations.

For simplicity, we assume that the dynamics of the physical sub-system are linear and free of perturbations, and are given by

$$\mathbf{x}^{\cdot}\,(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t)\ \mathbf{y}(t) = \mathbf{C}\mathbf{x}(t)\ , \ (1)$$

Where **x** is an M-vector representing the system state; **u** is the Nc-dimensional vector of control actions where unc stands for the control action of controller nc; **y** is the Ns dimensional vector of observations at the sensors where yns is the observation at sensor ns. The dimensions of matrices **A**, **B** and **C** are M ×M, M ×Nc and Ns ×M, respectively. Note that the assumption of linear dynamics is valid for linear systems and is also effective for nonlinear systems when the system state deviates only slightly from an equilibrium point. It is much more challenging to study the general nonlinear case, which is a topic for future work. We also note that we do not consider random perturbations, such as noise in the observation, in the system. The only uncertainty is the initial condition in the system dynamics (otherwise, if the initial state is also known, there is no need for communications). The study of this deterministic system will be extended to stochastic systems.

B. Model of Communication Network

We assume that the Nc controllers and Ns sensors are all equipped with communication interfaces, either wired or wireless. There are also Nr relay nodes in the communication network, which can help the delivery of observations from the sensors to the controllers. We denote the three types of nodes by {nc} nc=1,...,Nc , {ns} ns=1,...,Ns , and {nr} nr=1,...,Nr , where the subscripts represent the types of nodes. We call the data flow from a sensor to a controller a connection. The topology of the communication network composed of the three types of nodes is known in advance. For the wired network, the topology is determined by the existence of wired links; for the wireless network, the topology is determined by the distances among the nodes. We use the notation a ∼ b to denote that nodes a and b are directly connected in the communication network.

We make the following assumptions on the communication network throughout the paper in order to simplify the analysis:

- Fluid Traffic
- Bandwidth Constraint
- Routing Mode Switching

III. MULTICAST ROUTING WITHOUT DELAY

In this section, we study multicast routing under the assumption that there is no delay and the observation can be delivered to the controller instantaneously without any loss. The assumption of no delay simplifies the analysis, which provides insights for the more complicated case with non-negligible delay. This assumption is also valid when the communication speed is very fast, compared with the dynamics of the physical system. For example, the electron mechanical dynamics could be on the order of seconds (Page 6, [21]), while the wireless network could deliver the data in milliseconds. The case of non-negligible delay will be studied in the next section.

A. Decentralized Control

Here, we introduce the mechanism of decentralized control in the cyber physical system.

1) Single Routing Mode Case: We first consider the single routing mode. We assume that a linear feedback control is employed for the cyber physical system, which is given by [28].

2) Multiple Routing Modes: Recall that there are totally Q routing modes. We denote by **K**q the feedback gain matrix corresponding to the q-th routing mode.

B. Optimization Problem Formulation

Here, we study how to select the routing mode(s) in order to stabilize the cyber physical system using the decentralized feedback control.

1) Single Routing Mode: We first consider the case in which a single routing mode can stabilize the system. The key challenge is how to determine the set of destinations. Given an arbitrary routing mode, if the feedback gain matrix **K** is determined in advance6, we can simply check the eigen values of $\tilde{\mathbf{A}}$: if the real parts of all eigen values are in the left half.

2) Multiple Routing Modes: It is possible that a single routing mode may not stabilize the cyber physical system or may not be rigorously shown to stabilize the system dynamics. In this case, we need to consider multiple routing modes and let the communication network switch among these modes.

C. Heuristic Solution

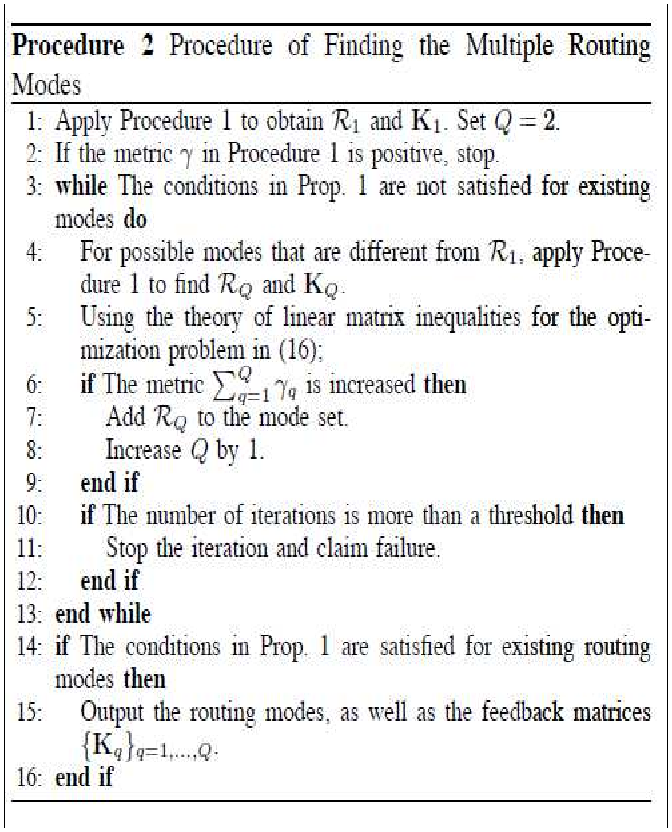
As we have explained, it is difficult to solve the optimization problems in (12) and (15) analytically. Hence, we propose heuristic algorithms for these problems.

1) Single Routing Mode: For the single routing mode case, we search for the connections between the sensors and controllers in a greedy manner. The basic strategy is, in each step, we add a new connection such that the objective function γ is maximized for the existing connections. The reason for the greediness is that the objective function is increased as much as possible at each step, under the constraints on the total communication resources. The details of the proposed heuristic algorithm are provided in Procedure 1.

Procedure 1 Procedure of Finding the Single Routing Mode

```
Initialize the initial routing mode $R$ as an empty set.
Initialize the unsearched connection set $U$ as all possible sensor controller combinations
while $U$ is nonempty do
    for All connections in $U$ do
        Check the feasibility of the connection subject to the Existing connections and the bandwidth constraint.
        if Feasible then
            Add the connection to the existing connections to obtain the temporary routing mode.
            Solve the matrix equation in (9).
            Solve the optimization problem in (10) using the LMI Tool and obtain the maximal $\gamma$.
        else
            Remove the connection from $U$.
        end if
    end for
    Choose the connection with the largest $\gamma$ and obtain the Corresponding $\mathbf{K}$.
    Find the shortest path from the nodes having the information of the sensor to the controller.
    Add the connection and the routing information to $R$.
    Remove the connection from $U$.
end while
```

2) Multiple Routing Modes: Again, it is very difficult to solve the optimization problem in (16). We propose a heuristic approach that is similar to Procedure 1 for the single mode case. The procedure is also greedy.



Procedure 2 Procedure of Finding the Multiple Routing Modes

```
Apply Procedure 1 to obtain $\mathcal{R}_1$ and $\mathbf{K}_1$. Set $Q = 2$.
If the metric $\gamma$ in Procedure 1 is positive, stop.
while The conditions in Prop. 1 are not satisfied for existing modes do
    For possible modes that are different from $\mathcal{R}_1$, apply Procedure 1 to find $\mathcal{R}_Q$ and $\mathbf{K}_Q$.
    Using the theory of linear matrix inequalities for the optimization problem in (16);
    if The metric $\sum_{q=1}^{Q} \gamma_q$ is increased then
        Add $\mathcal{R}_Q$ to the mode set.
        Increase $Q$ by 1.
    end if
    if The number of iterations is more than a threshold then
        Stop the iteration and claim failure.
    end if
end while
if The conditions in Prop. 1 are satisfied for existing routing modes then
    Output the routing modes, as well as the feedback matrices $\{\mathbf{K}_q\}_{q=1,\ldots,Q}$.
end if
```

Note that the proposed routing algorithm has addressed the two challenges discussed in the introduction, implicitly or explicitly, within the framework of optimization:

- Uncertain destinations: In the optimization, each sensor can find the destination controllers that mostly contribute to the objective function in the optimization problem, within the constraints on the communication resources.
- Multiple routing modes: The algorithm can find multiple routing modes that stabilize the system dynamics, if a single routing mode cannot.

IV. MULTICAST ROUTING WITH SMALL DELAYS

In the previous section, we ignored the delay in order to simplify the analysis. However, in practice, there always exists communication delay. Hence, based on the discussion of the no delay case, we will study the multicast routing algorithm when the delay is non-negligible. We will first write down the dynamics when delay exists. Then, we formulate the routing problem as an optimization problem and finally propose a heuristic algorithm similar to Procedure 1. Note that we consider only the single routing mode in this section, for simplicity of analysis.

A. Dynamics with Delay
B. Optimization Problem Formulation.

V. APPLICATION IN DEG VOLTAGE CONTROL OF SMART GRID

Recent years have witnessed the rapid growth of DEGs due to the pressing demand for reliability and security of the electricity power grid. DEGs are coupled into the main power network at the points of common coupling (PCCs). An important task of DEGs is to control the voltages at the PCCs or remote locations, which can be accomplished by power electronics (PE) interfaces. Each PE interface consists of an inverter and a DC-side capacitor. There is a coupling inductor between the inverter and the rest of the system. Note that the voltage control of a DEG is different from that of traditional generators in large power grids.

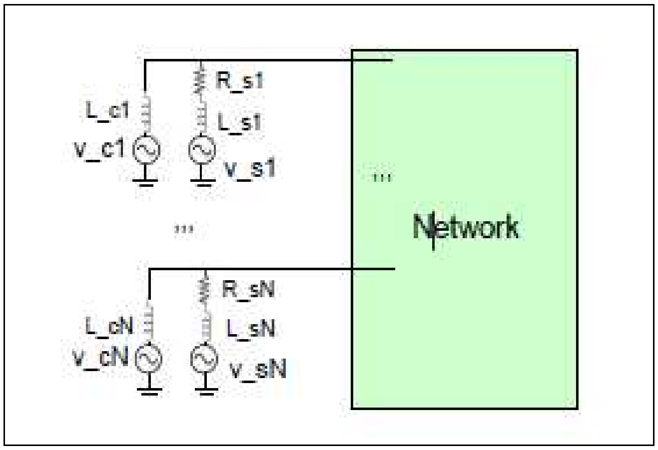


Fig. 2. An illustration of the model of multiple DEGs connecting to the power network

In this paper, we adopt the model of a power network from [17], as shown in Fig. 2. We assume that there are N DEGs, modeled as voltage sources whose voltages are denoted by {vn c (t)} n=1,...,N . A coupling inductor exists between each DEG and the rest of the network. There could be a voltage source (substation) at each bus, whose voltages are denoted by {vn s (t)} n=1,...,N . When there is no source at bus n, we can set vn s = 0. To simplify the analysis, we assume vn s = 0 for all n = 1, ...,N; i.e., only DEGs are connected to the power network. Then, the nodal voltage equations are given by (in the domain of Laplace transformation).

VI. NUMERICAL SIMULATION

In this section, we study a simple 4-bus example and demonstrate the performance of the algorithms proposed in this paper.

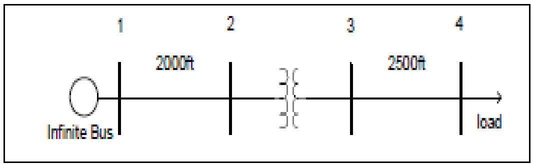


Fig. 3. An illustration of the four bus model

A. Simulation Configuration

1) Power Grid: For simplicity, we consider a simple example, a 4-bus model of the distribution test feeders proposed by the IEEE distribution test feeder working group, which is illustrated in Fig. 3. The details can be found in [10]. The admittance matrix is given in (30) in the top of next page. We obtain the system matrices, which are given by

$$\mathbf{A}=\begin{pmatrix} 0.1759 & 0.1768 & 0.5110 & 1.0360 \\ -0.3500 & -0.0000 & -0.0000 & -0.0000 \\ -0.5442 & -0.4748 & -0.4088 & -0.8288 \\ -0.1197 & -0.5546 & -0.9688 & -1.0775 \end{pmatrix} \times 10^3, \quad (31)$$

and

$$\mathbf{B}=\begin{pmatrix} 0.0008 & 0.3342 & 0.5251 & -1.0360 \\ -0.3500 & -0.0000 & -0.0000 & -0.0000 \\ -0.0693 & -0.0661 & -0.4201 & -0.8288 \\ -0.4349 & -0.4142 & -0.1087 & -1.0775 \end{pmatrix} \times 10^3. \quad (32)$$

2) Communication Network: We assume that there are two arrays of relay nodes, each containing 4 nodes, between the sensors and controllers, thus forming a 4×4 array in the plane, as illustrated in the upper part of Fig. 4. Hence, each packet from a sensor must pass three hops to reach a controller. For Simplicity, we assume that each node can forward the packet of only one sensor, i.e., wab = 1; the transmission of one packet can reach all next-hop neighbors. We also assume that each controller can receive packets from multiple relay nodes simultaneously.

B. Numerical Results

Based on the above configuration of the power network and communicate network, we carry out simulations for multiple situations. Throughout all simulations, we fix cK = 5; i.e., the 2-norm of the feedback gain matrix **K** cannot be larger than 5. Note that we used the robust control toolbox of Mat lab to solve the optimization problems with LMI constraints.

1) Single Mode Case - No Delay: We first tested the performance of Procedure 1 when we consider only one routing mode. The network topology is given in the upper part of Fig. 4. The routing scheme obtained from Procedure 1 is given in the lower part of Fig. 4. We observe that it is not necessary for each controller to receive packets from all sensors.

For example, controller 4 does not receive any reports from sensors 1 and 2.

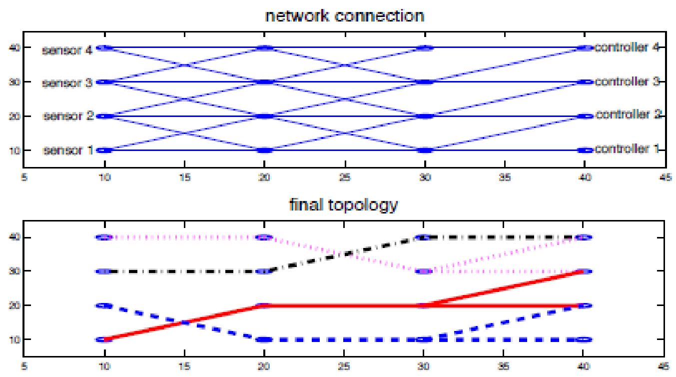


Fig. 4. Network topology obtained from Procedure 1 in the single-mode and delay-free case.

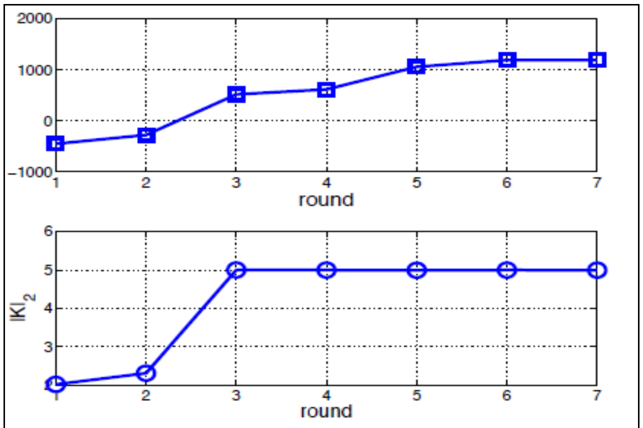


Fig. 5. The evolution of γ and $||\mathbf{K}||_2$ in the single-mode and delay-free case.

2) Multiple Mode Case - No Delay: From the network topology in Fig. 4, which can be stabilized by a single routing mode, we remove some links and result in the topology. The routing scheme obtained from Procedure 1 is also shown fig 7 .However, from Fig. 8 which shows the evolution of γ and _**K**_2, we observe that the routing scheme does not result in a stabilizing feedback control since γ is always negative. Note that this does not mean that the topology in Fig 7 cannot be stabilized by a single routing mode since Procedure 1 does not guarantee an optimal routing scheme; however, at least our current routing algorithm is unable to find a single stabilizing routing scheme for the network topology.

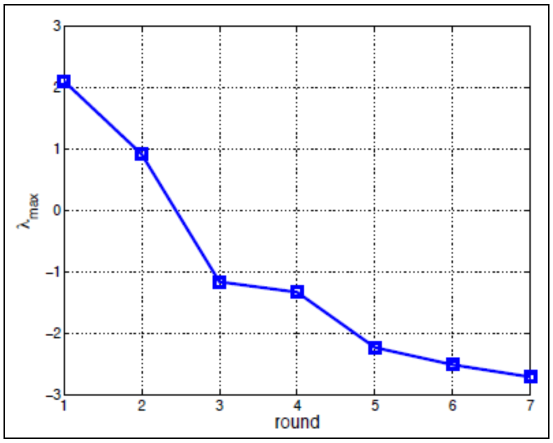


Fig. 6. The maximum eigenvalue of the linear dynamics

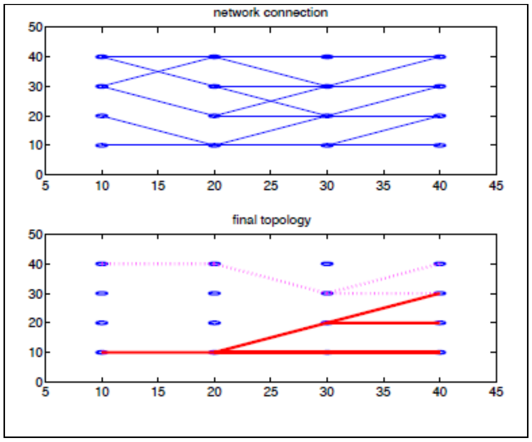


Fig. 7. Network topology obtained from Procedure 1 in the single-mode and delay-free case: routing failure.

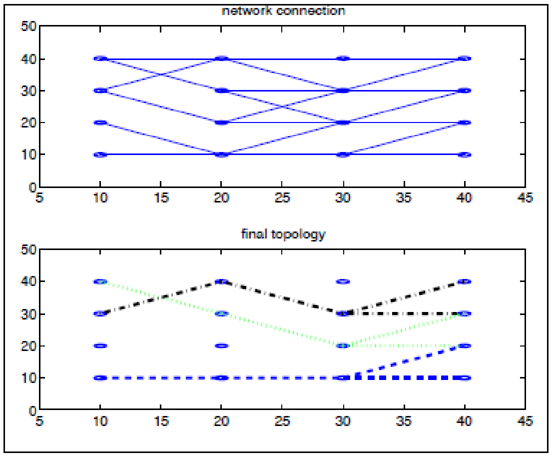


Fig 8. Network topology when the delay is non-negligible

VII. CONCLUSIONS

In this paper, we have studied multicast routing for decentralized control in cyber physical systems and applied the proposed algorithms to distributed voltage control in smart grid. To address the challenges of uncertain destinations and multiple routing modes, we have formulated the routing problem as a series of optimization problems, using the theories for both cases; we have proposed heuristic greedy algorithms to solve the optimization problems. As a case study, we have considered voltage control in a 4-bus power grid having a communication network. Numerical simulation results have shown that our proposed algorithms can find stabilizing routes for the power grid.

VIII. APPENDIX JUSTIFICATION OF GREEDY ALGORITHM

Proposition: Consider a decoupled system in which the matrices **A**, **B** and **C** are all diagonal. Assume that there is only one relay node, which can be considered as a base station, as illustrated in Fig. 9. The sensors and controllers cannot talk to each other directly. Each connection must route through the base station. The base station can support at most Q connections. Then, the algorithm in Procedure 1 is optimal for the following optimization problem:

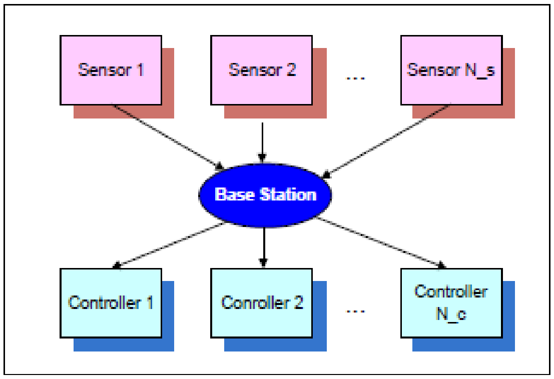


Fig 9: An illustration of the star topology in Prop. 4

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