A New Approach for Finding Minimum Delay Control Centers of Control Networks

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Abstract—**A Control network denotes a group of devices to monitor, control, communicate and manage system operation. In a wide area control network, decision making location is known as control center. The communication delay (latency) between a node and a control center in a control network has been characterized by network topology, transmission media characteristics and location of control center.**

The aim of this investigation is to propose an algorithm which tries to find an appropriate control center location such that all nodes' latencies are minimized and equalized. The simulation results show that if a control center with determined latency limitation exists, the proposed algorithm can locate it. Otherwise, the entire control network can be partitioned into multiple areas such that the latency limitation in each area has been satisfied.

Control Network; Control Center; Controlled Area; Communication latency

I. Introduction

Online information is essential for both secure operation and control of a system. System information can be shared through a communication network for operating or controlling reasons. Control network is responsible for exchanging data and information among different entities in the system for controlling this system. According to the definition, proposed by the Echelon Corporation, "a control network is any group of devices working in a peer-to-peer fashion to monitor sensors, control actuators, communicate reliably, manage network operation, and provide complete access to network data" [1]. Water and energy control networks, building management system (BMS) networks, and traffic light control networks are some instances of control networks.

Indeed, control network of a system is similar to human's neural network. As in case of failure or mal functioning of neural network paralyzed may happen, failure of a control network may cause serious problems for the system operation and control. Consequently, Special attention should be paid to control network of a system and its critical characteristics. Control networks may be varying in the number of nodes, the network topology, and their complexity. These differences result from the differences in the systems in which control networks should link them.

Communication networks, in accordance with their ranges, can be classified as local area networks (LAN) and wide area networks (WAN). This classification can be also generalized to control networks. Therefore, control networks can be classified as control LANs and control WANs.

In a control process, after acquiring data from various measurement devices and sensors, appropriate decisions should be made and an action should be performed. In a control WAN, decision making location is known as control center [2], [3] and controlled area is referred to as the location where an action has been performed [4].

As explained above, measurement process is a part of control process; therefore, control process is beyond the measurement process. Consequently, some network parameters, which are not critical and vital for monitoring process, have become very important for control process. Control network reliability, network latency (delay) and bandwidth are major parameters.

The latency of a controllable area in a control network will be influenced by the topology of control network, the transmission media characteristics, and the media length between this controllable area and control center. It is clear that the location of control center in a network characterizes the distance between controllable areas and control center. In control LANs, network topology has more affect on latency [5], whereas propagation delay, which is caused by transmission media, has more influence on latency of control WANs [6].

Considering the above-mentioned facts, it can be concluded that most of control networks (such as power and water control networks) have performed the critical online control process; hence, they are strongly delay-sensitive. However, due to the range growth in control WANs, location of control centers has several influences on communication latency of these control WANs. As a result, this investigation aims to present an algorithmic method for finding minimum delay control center for a given tree control WAN.

This paper is organized as follows. Section II proposes latency calculation in control networks. The statement of the problem is defined and formulated in section III. In the same section, new indices, related to communication latency, are defined as well. Then, new algorithm has been introduced in order to find the minimum delay control center. Section IV represents a case study and its simulation results. The paper ends with concluding remarks in section V.

II. Latency Calculation of Control Networks

The transmitted packets in a control network (such as power system control network) differ from packets in other computer networks. The packets may be in a low volume and periodical [7]. Communication latency in a control LAN strictly depends on communication network topology [5]. In a control WAN, on the other hand, location of control center is responsible for some infrastructural latency including propagation delay and routing delay. Consequently, infrastructural latency, caused by transmission media and routers, should be more investigated in control WANs. In the current study, at first, power system control WAN is considered and its related communication latency is investigated. Then, the proposed method for calculating latency has been generalized to other control WANs.

In [6], Jonathan and his colleagues represented the total signal latency in a power system control network as follows:

$$T = T_s + T_b + T_p + T_r \tag{1}$$

where, T_s is the serial delay, T_b is the between packet delay, T_p is the propagation delay, and T_r is the routing delay.

Due to control WANs similarities, equation 1 can be generalized to the most other control WANs. Inspection of equation 1 denotes that some amount of latency is caused by infrastructure (T_p and T_r) and can be assumed as infrastructural latency. Propagation delay can be considered as passive latency of infrastructure, while routing delay can be taken into consideration as active delay of infrastructure.

Propagation delay can be calculated by division length of transmission media by the velocity of transmission media. Therefore:

$$T_p = \frac{l}{v} \tag{2}$$

where, l is the length of media, and v is the velocity at which the data are sent through it (e.g., 0.6c to c, where c is the speed of light).

In [6], the path from a node to the control center is traced, and all of the routing delays are added up, hence; total routing delay for a node can be represented as follows:

$$T_r = \sum_{i=1}^{N} T_{i^{th}\ Router} \tag{3}$$

where, $T_{i^{th}\ Router}$ is the latency of i^{th} router and N is the number of network routers in the path between a node and control center. N is also known as "network hops".

To simplify latency calculation, only the infrastructure latencies are considered; therefore, we assume that the T_s and T_b are constant. It is also assumed that reliability values of all routers are the same. Thus, the equation 1 can be summarized as follows:

$$T = Const + \frac{l}{v} + N \times T_{Router} \tag{4}$$

From equation 4, it can be easily concluded that latency of a control WAN will be increased if l and N are increased.

III. Problem Definition and Formulation

The purpose of this study is to find a central control center for a given tree control network such that latency limitations for all nodes have been satisfied. Finding a control center for a telecommunication network is not such a new idea. Cahit and his colleague [8], introduced an algorithm to find a control center for tree networks under a given reliability index m. The index m is the maximum number of allowable nodes that may be unable to communicate with control center, due to the failure of a single link randomly. An examination of the algorithm which is introduced in [8] indicates that reliabilities of active devices are only considered and communication latencies (active and passive ones) are not investigated. Thus, due to the fact that some control applications are strongly delay-sensitive, we have proposed a method to find a minimum delay control center for a given control WAN.

To carry out our investigation, two indices have been defined and assigned to each node. *NoR* index, represents the number of routers between a node and control center in a tree network. *NoR* is also referred to as a node's "network hops". Another defined index is *LoM*. *LoM* implies the length of transmission media between a node and control center. According to equation 4, infrastructure latency consists of two parts and can be related to *NoR* and *LoM* values as follows:

$$T_{infra} = \frac{LoM}{v} + NoR \times T_{Router} \tag{5}$$

An examination of equation 5 shows that, the decline in *LoM* and *NoR* indices causes latency reduction. Consequently, an algorithmic method can be illustrated which tries to minimize and equalize *LoM* and *NoR* by locating control center. The next subsection is going to describe the proposal algorithm.

A. Proposal Algorithm

Proposed algorithm is the generalization of the method which has been represented in [8]. Lets $N(t_0)$ denote a control network with n node and n-1 links. The tree information should be represented by adjacency matrix. Adjacency matrix for $N(t_0)$ is an n dimension matrix whose arrays are defined as follows:

$$a_{ij} = \begin{cases} 1 & f\ i^{th}\ node\ connected\ to\ j^{th}\ node \\ 0 & otherwise \end{cases} \qquad a_{ii} = 0 \tag{6}$$

In Addition to adjacency matrix, the algorithm needs distance matrix. The distance matrix is similar to adjacency matrix in which any of its arrays represents the distance between two nodes.

Our proposal algorithm has started from end nodes, which have been linked to the network by only one links. The *NoR* and *LoM* indices of these nodes have been updated and then these nodes have been removed from network and after that, they have been merged into their upper nodes. Hereafter, upper nodes point to removed nodes; so, whatever happens for indices of upper nodes is also generalized to indices of merged nodes. This process repeats until the remaining network only consists of one node or two nodes. The basic steps of the proposed algorithm are listed below:

1) Latency Vector ($\hat{T}$), NoR Vector ($N\hat{o}R$) and LoM Vector ($L\hat{o}M$) are created and zero is assigend to all of their arrays.

2) End nodes are found.

3) End nodes are merged into their upper nodes. NoR values of them added to one, and length of only connected links added to their LoM values.

4) End nodes have been removed from control network, and adjancency matrix has been updated.

5) Delay Vector has been updated by using $N\hat{o}R$ and $L\hat{o}M$ vectors through equation 5.

6) Latency limitation is checked. If limitation is satisfied, steps 2 to 7 are repeated, else algorithm is stopped.

7) If all rows of updated adjacency matrix consist of one array, algorithm will be stopped.

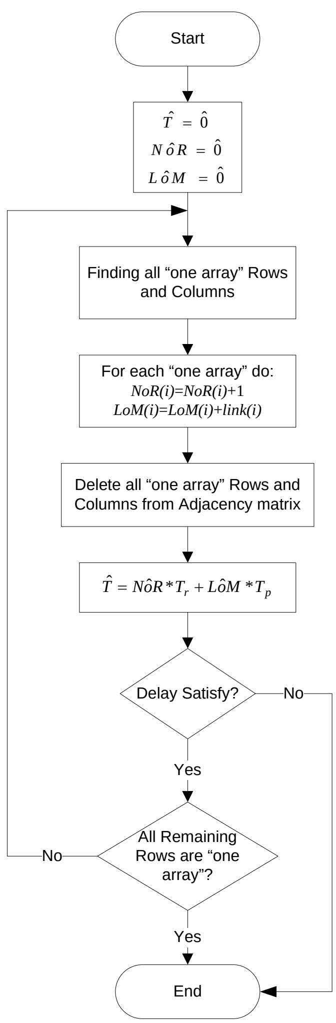

Figure 1. Proposed Algorithm for Finding Control Center.

This algorithm is illustrated in Fig. 1. The algorithm may be stopped for two reasons: either all rows of adjacency matrix consist of one array, or when latency limitation is dissatisfied. If algorithm has been stopped due to former reason, two cases may happen: one or two node(s) remain in adjacency matrix. In the case of remaining one node, this node will be the answer and can be opted as control center. Otherwise (remaining two nodes in former reason, or stopping by latter reason), the proposed algorithm only reduces control center candidate. In other words, some merged nodes are eliminated from candidate list, but the control center finding problem may still have an answer.

Remaining candidates should be checked by a reverse way (which was used previously) one by one. Breadth-First Search (BFS) algorithm is an effective way to traverse a graph by visiting all the nodes connected directly to a starting node (one of candidate nodes here) [9]. By Using BFS algorithm, *NoR* and *LoM* values can be estimated from a candidate node to each node. To clarify this, a case study will be illustrated in the next section.

IV. Case Study and Results

In this section, a case study is described in order to demonstrate our approach. A tree control network represented in Fig. 2 is considered. This tree network consists of 12 nodes and 11 branches.

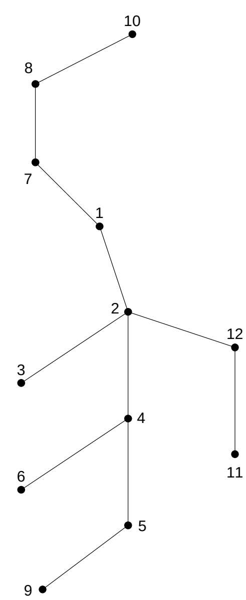

Figure 2. Sample Control Network.

Distance matrix of considered tree network is shown in (7). Note that the length is based on kilometer.

$$D = \begin{bmatrix} 0 & 46 & 0 & 0 & 0 & 0 & 303 & 0 & 0 & 0 & 0 & 0 \\ 46 & 0 & 46 & 244 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 70 \\ 0 & 46 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 244 & 0 & 0 & 128 & 244 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 128 & 0 & 0 & 0 & 0 & 93 & 0 & 0 & 0 \\ 0 & 0 & 0 & 244 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 303 & 0 & 0 & 0 & 0 & 0 & 0 & 151 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 151 & 0 & 0 & 256 & 0 & 0 \\ 0 & 0 & 0 & 0 & 93 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 256 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 200 \\ 0 & 70 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 200 & 0 \end{bmatrix} \quad (7)$$

For illustration purposes, it is assumed that all routers have the same routing delay (1 ms). It is also assumed that the transmission media velocity is equal to 0.6. We try to find control center for two different latency limitations; 7 ms and 6 ms.

A. Case 1

This case is proposed to find central control center in which latencies are less than or equal to 7 ms. To carry out this, the proposed algorithm runs for control network (shown in Fig. 2). The first set of end nodes is {3,6,9,10,11}. These nodes are merged into {2,4,5,8,12} nodes, respectively. Remaining nodes in each step of algorithm are shown in (8). The algorithm has been stopped since only two linked nodes have remained in adjacency matrix.

$$\begin{aligned} Step1 &: [1\ 2\ 4\ 5\ 7\ 8\ 12] \\ Step2 &: [1\ 2\ 4\ 7] \\ Step3 &: [1\ 2] \end{aligned} \quad (8)$$

NoR and *LoM* values have been updated in each step. Thus, latency vector ($\hat{T}$) has been calculated in each step by using equation 5.

$$\hat{T}_{Step1} = \begin{bmatrix} 0 \\ 0 \\ 1.2556 \\ 0 \\ 0 \\ 2.3556 \\ 0 \\ 0 \\ 1.5167 \\ 2.4222 \\ 2.1111 \\ 0 \end{bmatrix} \quad \hat{T}_{Step2} = \begin{bmatrix} 0 \\ 0 \\ 1.2556 \\ 0 \\ 1.7111 \\ 2.3556 \\ 0 \\ 1.8389 \\ 3.2278 \\ 4.2611 \\ 3.5000 \\ 1.3889 \end{bmatrix} \quad \hat{T}_{Step3} = \begin{bmatrix} 0 \\ 0 \\ 1.2556 \\ 2.3556 \\ 4.0667 \\ 4.7111 \\ 2.6833 \\ 4.5222 \\ 5.5833 \\ 6.9444 \\ 3.5000 \\ 1.3889 \end{bmatrix} \quad (9)$$

Inspection of latency vectors illustrated in (9) shows that, the latency limitation is satisfied. But $\hat{T}_{Step3}$ denotes the latencies between {7,8,10} nodes-to-node 1, and the latencies between {3,4,5,6,9,11,12} nodes-to-node 2. Actually, nodes 1 and 2 are two candidates for central control center. However, these two candidates should be examined by BFS algorithm. Estimated delay vectors for nodes 1 and 2; which are resulted from BFS algorithm, are shown in (10). Examination of (10) implies that only node 1 can be opted as an appropriate central control center such that all nodes latency is less than 7 ms.

$$\hat{T}_{node1} = \begin{bmatrix} 0 \\ 1.2556 \\ 2.5111 \\ 3.6111 \\ 5.3222 \\ 5.9667 \\ 2.6833 \\ 4.5222 \\ 6.8389 \\ 6.9444 \\ 4.7555 \\ 2.6444 \end{bmatrix} \quad \hat{T}_{node2} = \begin{bmatrix} 1.2556 \\ 0 \\ 1.2556 \\ 2.3556 \\ 4.0667 \\ 4.7111 \\ 3.9389 \\ 5.7778 \\ 5.5833 \\ 8.2000 \\ 3.5000 \\ 1.3889 \end{bmatrix} \quad (10)$$

B. Case 2

This case has more strict conditions. All latency of nodes should be less than or equal to 6 ms. The algorithm runs again, but in this case, the algorithm has been stopped in step 2 because of latency dissatisfaction (see (9)). In Step 2, the end nodes in adjacency matrix are 4 and 7. BFS algorithm should be used to estimate latency vectors in which starting nodes are 4 and 7. The results are shown in (11).

$$\hat{T}_{node4} = \begin{bmatrix} 3.6111 \\ 2.3556 \\ 3.6111 \\ 0 \\ 1.7111 \\ 2.3556 \\ 6.2944 \\ 8.1333 \\ 3.2278 \\ 10.5556 \\ 5.8555 \\ 3.7444 \end{bmatrix} \quad \hat{T}_{node7} = \begin{bmatrix} 2.6833 \\ 3.9389 \\ 5.1944 \\ 6.2944 \\ 8.0056 \\ 8.6500 \\ 0 \\ 1.8389 \\ 9.5222 \\ 4.2611 \\ 7.4389 \\ 5.3278 \end{bmatrix} \quad (11)$$

Careful study of (11) shows that, none of the remaining candidates can be chosen as central control center since the latency limitation is not satisfied (bigger than 6 ms). Consequently, centralized control center does not exist, and only decentralized control centers can communicate with acceptable latency. Node 7 can be assumed as area control center for set {1,8,10}, and node 4 can be supposed as area control center for set {2,3,5,6,9,11,12} (Fig. 3).

Table I shows a representation of area information and the latency values of nodes (in ms). Note that the values have been rounded, and ACC is abbreviated for Area Control Center.

TABLE I. AREA INFORMATION IN CASE 2

	Area Information									
	Area 1							***Area 2***		
ACC	4							7		
Node	2	3	5	6	9	11	12	1	8	10
Delay	2.4	3.6	1.7	2.4	3.2	5.9	3.7	2.7	1.8	4.3

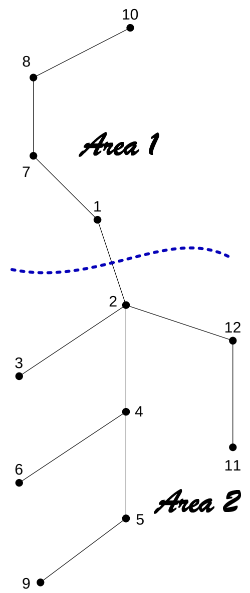

Figure 3. Network Partitioning in Case 2.

In fact, whatever happens in this case can be explained as follow. Our proposal algorithm starts from end nodes and reduces the size of network. Reduction process continues until the latencies of eliminated paths are less than the specified limitation. After that, remaining nodes may be chosen as control center and this should be examined by BFS algorithm. Indeed, proposed algorithm has strictly reduced the size of control center candidates and BFS has been done for fewer nodes.

V. CONCLUSION

A control network is a network of nodes that monitors sensors, controls actuators and manages system operations. Control networks, according to their ranges, can be classified as control LANs and control WANs. In a control WAN, decision making location is known as control center. In such a system, location of control center characterizes the distance between nodes and control center.

Latency of a node in control network will be influenced by the network topology, transmission characteristics and transmission media length. Propagation delay, as a cause of transmission media length, has become higher in control WANs. Consequently, the location of control center in a control WAN has become extremely crucial, especially for characterizing latency of network nodes.

Additionally, most of control WANs, such as water and power control WANs; have performed critical online control applications. Hence, they are strongly delay-sensitive and system data should communicate with these applications under the specified latency limitation. As a result, a new method should be introduced to solve latency problem for control WANs.

This paper proposes a new algorithm for finding a minimum delay control center in a tree control WAN. It is worth noting that in this study only propagation and routing delays are considered. Therefore, two indices, which are directly corresponded to these delays, are defined. Proposed algorithm has started from end nodes and the nodes indices have been updated. Then, end nodes have been removed from network and the algorithm has run for new network. This process repeats until latency limitation has been dissatisfied.

Our proposal algorithm may directly respond and control center has been achieved. Otherwise, control center candidates have been at least reduced by proposed algorithm. Then, the candidates of control center should be examined by BFS algorithm. BFS algorithm has acted in contrast with proposed algorithm. Proposed algorithm has started from end nodes and indices have been updated, while BFS has started from a candidate node and indices has been updated.

The simulation results show that the proposed algorithm is an effective way for examination of propagation and routing delays in control WANs. If control center with determined latency limitation exists, the appropriate location for control center will be located by the proposed algorithm (in combination with BFS algorithm occasionally). Otherwise, area partitioning can be suggested by our proposal algorithm such that each area has its own control center (ACC) and latency limitation for each area has been satisfied.

The proposed algorithm has examined communication latencies and control center has been located based on infrastructure latencies, whereas previous algorithm which is introduced in [8] only focuses on active devices latency. While a list of candidates for control center has been suggested by previous algorithm, our proposed method has found the exact location of CC (occasionally ACC). Considering all the above facts, it can be concluded that the proposal algorithm is an effective way to locate control centers based on infrastructure latencies.

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