Congestion control method for Clustered Sensor Networks Based on T-S fuzzy model

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Abstract: The many to one communication mode of clustered sensor network is prone to information transmission interference, which leads to network data transmission congestion, resulting in frequent network dynamic changes and resource constraints. In order to solve the above problems, this paper proposes a congestion control method based on T-S fuzzy model for Clustered Sensor Network, so as to achieve reasonable control and processing of massive data in the congested network environment. Based on the analysis of the characteristics of clustering sensor networks, this paper describes the strategies of congestion detection and congestion avoidance, and focuses on the introduction and analysis of typical congestion relief algorithms based on rate control, traffic scheduling and transmission scheduling. Finally, the development trend of congestion control technology is prospected. Experiments show that clustering based on T-S fuzzy model is feasible. The congestion control method of sensor network has high control effect in the practical application process, and fully meets the research requirements.

1. Introduction
Clustering sensor network (CSN) cooperatively perceives and processes the information of sensing objects by deploying large-scale micro sensor nodes in the monitoring area, and sends the information to users in a self-organizing multi-hop wireless communication mode[1]. Clustering sensor network is a task-based network which covers the perception, processing and transmission of information[2]. Its quality of service includes not only the transmission quality of information, but also the perception quality and intra network processing quality of information[3]. For the quality of information transmission, clustering sensor networks tend to pay more attention to the set statistics of non end-to-end communication from a group of nodes activated by event triggering to the sink node of clustering sensor, such as aggregation delay, aggregation packet loss rate, aggregation bandwidth, rather than the end-to-end index between a sensor node and the sink node of clustering sensor Network congestion control method can better deal with massive network data effectively, improve the quality of network operation, and ensure the effect of data processing[4].

2. Congestion control method for Clustered Sensor Networks
2.1. load capacity control algorithm for Clustered Sensor Networks
Congestion control is closely related to network carrying capacity. Clustering sensor network carrying control can inhibit the source to send data and play the role of carrying capacity control. On the contrary, good carrying capacity control can avoid or delay congestion transmission. There are some differences between network congestion control and carrying capacity control. The former is a problem related to the overall situation of the network, aiming at solving the bottleneck problem of
router and other intermediate link equipment\cite{5}. Its rules are social and require fairness and rationality. The latter only involves the end-to-end propagation from the source to the destination, which is to ensure that the data sent by the source does not exceed the receiving capacity of the destination and solve the bottleneck problem of the destination\cite{6}. This is the individual behavior of the two, there is no fairness problem. Cluster sensor node is usually a tiny embedded device, which is the core device of cluster sensor\cite{7}. Clustering sensor nodes are generally composed of four parts: sensing detection system, processor system, RF transceiver system and power management system. Cluster sensor sensing system unit is usually composed of two parts: sensor chip and digital to analog conversion chip\cite{8}. The sensing information of cluster sensor chip is generally analog signal, which can be transmitted in the network after A/D conversion. The processor system is usually composed of embedded microprocessor, RAM memory and necessary peripherals\cite{9}. The processor unit is responsible for the data processing, transmission scheduling, transceiver control of the whole node. Among them, the processor is generally low-power micro embedded processor, such as arm, 8051 microcontroller, AVR microcontroller of ATMEL company. Now, the more advanced processing system can be transplanted operating system, generally embedded operating system, such as Linux operating system, TMY OS operating system. RF transceiver system is composed of wireless communication module, which is responsible for data transmission between nodes, exchange of control information and detection of channel related information\cite{10}. RF Transceivers with low cost, low power consumption and short distance transmission are usually used, such as CC series of TI company, VLSI of Nordic company, atrf series of ATMEL company\cite{11}. The power supply module mainly provides the necessary energy for the normal operation of the node, generally using micro battery or dry battery. In addition, due to the special application requirements of some sensor nodes, the hardware structure also includes some auxiliary modules, such as positioning, ranging, mobile, self destruction devices and so on\cite{12}. Based on this, the node structure of clustering sensor network is optimized, as shown in the figure below:

In the CPU of cluster sensor nodes, communication protocol standards need to be transplanted. At present, ZigBee, WirelessHART, ISA and so on are the main protocol stacks used in clustering sensor networks. These protocol stacks have common characteristics: low power consumption, low cost, low complexity, low rate, high reliability, simple networking, flexible and convenient use\cite{13}. Similar to TCP / IP model, the protocol stack of clustered sensor network is also divided into five layers, which are application layer, transport layer, network layer, MAC layer and physical layer from top to bottom. In parallel, there are some special modules of WSN, such as security management module, task processing module, information management module and power management module\cite{14}. Based on this, the control protocol stack of clustering sensor network is designed, as shown in the figure.
In the protocol of clustering sensor network, it is mainly responsible for signal receiving and sending, signal inversion detection and control. In general, the transmission media used are electromagnetic wave, infrared ray, light wave, etc \cite{15}. The channel link capacity can be consumed as much as possible. The MAC layer is responsible for encapsulating the packets from the upper layer into frames for frame detection and error control, media access, etc. It is also responsible for controlling the physical layer, including channel selection and wireless signal monitoring. The MAC layer of sensor networks generally supports reliable point-to-point and point to multipoint communication. The function of the network layer is to maintain the sub path and route. Generally, there is no special routing node in WSN. The data of the source node is forwarded to the sink node through the middle node, and the middle node 0 is also the data collection node. The transport layer is responsible for the reliable transmission control of data flow and plays a role in ensuring the quality of communication service. Congestion detection mechanism is the beginning of congestion control in sensor networks, and it is also an indispensable step. High precision and low cost are the key to judge whether it is an effective congestion control mechanism.

2.2. Optimization of congestion control algorithm for Clustered Sensor Networks

The T-S fuzzy model is used to optimize the congestion control algorithm of cluster sensor networks. According to the communication network model of cluster sensor networks, the fluid flow model of congestion avoidance algorithm can be expressed as:
Where: $W_i(t)$ represents the window size of the $i$-th communication packet, $q(t)$ represents the queue length of the network packet at time $t$, $C(t)$ represents the effective bandwidth of the communication network, and $p(t)$ represents the packet identification probability at time $t$. $p_i$, represents the window conversion rate, where the first term represents the amount of window increase caused by bandwidth, and the second term represents the amount of window decrease caused by network congestion. If $M_i(t)$ is the congestion flag in cluster sensor network, when congestion occurs, its value is 1, otherwise it is 0. It can be seen from the above formula that the window size increases in the form of addition and decreases in the form of multiplication. Therefore, in order to prevent network congestion caused by node congestion in communication network, the reduction speed of window size is much higher than the increase speed\(^{[16]}\). At the same time, sensor nodes need to consume a certain amount of energy when transmitting data, so there is a certain attenuation in the use of communication channel\(^{[17]}\). When considering the channel attenuation, the window conversion rate needs to be further modified to:

$$
\tau_i(t) = T_{p,i} + \frac{q_i(t)}{C(t)} W_i(t)
$$

$$
= \frac{1 - M_i(t)}{\tau_i(t)} - \frac{W(t) W[t - \tau_i(t)]}{2 \tau_i[t - \tau_i(t)]} p_i[t - \tau_i(t)] (1)
$$

Similarly, it can be deduced that the change rate of the length of the data queue in the node considering the communication state of the adjacent nodes is as follows:
\[ q(t) = \begin{cases} C(t) + \sum_{i=1}^{N} \frac{W_i(t)}{\tau(t)} \eta_i \left[ t - \tau_{ah, i}(t) \right] \left[ 1 - P_{dl,i}(t) \right] \eta_i(t), & q(t) > 0 \\ \max \left\{ 0, C(t) + \sum_{i=1}^{N} \frac{W_i(t)}{\tau(t)} \left[ t - \tau_{ah, i}(t) \right] \left[ 1 - P_{dl,i}(t) \right] \eta_i(t), \right. \\ \left. q(t) < 0 \right\} \] (4)

Where \( \tau_{ah} \) can be regarded as an integral multiple of \( \tau_0 \). \( \eta_i(t) \) and \( \eta_{\left[ t - \tau_{ah, i}(t) \right]} \) denote the congestion degree of adjacent nodes at corresponding time. \( M_i(t) \) stands for the flag bit of congestion, which is 0 when the node is not congested and 1 when the node is congested. In the formula, \( P_{dl, i}(t) \) represents the data loss rate caused by channel attenuation when the sensor node transmits to the previous node in downlink communication. Generally, in a short period of time, the value of \( P_{dl, i}(t) \) has little difference from \( P_{dl, i}(t) \) and can be approximately equal. As the congestion control model of clustering sensor network is a nonlinear structure model, it is very difficult to solve it directly\[19\]. After linearization, the control model of linear system is used to solve the problem, which can simplify the control difficulty and the solution process. We regard \( p, q \) as the state variable of the system and \( P \) as the input variable. For any group of parameters \( (N, C, T_0, P_{dl}, \eta) \), it is assumed that the stable operation point of the system is \( (W_0, q_0, p_0, \eta) \), and the relationship among them is as follows:

\[
\begin{aligned}
&x(t) = \sum_{i=0}^{M} A_i x(t-\tau_i(t)) + \sum_{i=0}^{M} B_i u(t-\tau_i(t)) + D_i y_i(t) + D_p y_0(t) \\
z(t) = Hx(t) \\
z_i(t) = \sum_{i=0}^{M} C_{2i} x(t-\tau_i(t)) + \sum_{i=0}^{M} D_{2i} u(t-\tau_i(t)) \\
y(t) = \sum_{i=0}^{M} C_{3i} x(t-\tau_i(t)) + \sum_{i=0}^{M} D_{3i} u(t-\tau_i(t))
\end{aligned}
\] (5)

The design purpose of clustering sensor network is to keep the data length in the node queue within a certain range, which requires the control system to have the ability to resist the influence of external interference on the system while ensuring good robustness, so as to achieve the research requirements of effective treatment of network congestion.

### 2.3 Implementation of congestion control in Clustered Sensor Networks

The improved T-S fuzzy model is divided into network layout standby node, congestion detection, cooperative path establishment based on trigger node, stable data transmission, cooperative path release when congestion is released, standby node goes to sleep state. The flow chart of the algorithm is as follows:
In the T-S fuzzy model, each node in the network maintains the information table of the corresponding neighbor node. By receiving the RTS frame from the neighbor node, it obtains its own identification number, congestion factor, residual energy, the direct distance between the next hop node and the sink node, the data flow of the adjacent node, the distance from the congestion point, and the channel Occupancy. When the network congestion occurs and the cooperative path is established, based on the attribute value of each node and referring to a certain way, the most suitable node is selected to establish the cooperative path\cite{20}. After congestion relief, the path release node keeps low energy consumption and prolongs the network life cycle.

Network congestion is a phenomenon that the performance of the network will decline when too many packets exceed the carrying capacity of the network. For the convenience of research, the bearing capacity curve of clustered sensor network is shown, as shown in the figure below. When the network load does not exceed the knee point, the network throughput increases linearly with the network load. When the network load increases between the knee point and the cliff point, the network throughput no longer increases linearly with the load, but increases slowly; When the network load is greater than the average point, the network throughput decreases rapidly with the increase of network load. At the same time, network congestion can also be regarded as a state, that is, because there are too many data packets in the network or some sub networks in a certain period of time, the network enters a state of performance degradation. Based on the analysis of the load-carrying capacity curve of clustering sensor network, the congestion control method of clustering sensor network is designed. The specific change curve is as follows:
When the number of data packets in the network is small, all the data packets can reach the target node smoothly, and the network load is proportional to the composition of the transmitted data packets. However, as the network data packets gradually increase to a certain value, the network transmission performance will gradually reduce, or even become paralyzed. Congestion control is that network nodes take effective measures to avoid congestion when they detect the trend of congestion, or take measures to relieve congestion to the nodes that have congestion. Its purpose is to ensure that the effective data detected by each node converges smoothly to the sink node in the sensor network transmission data. Because the congestion control of sensor network may involve the nodes of the whole sensor network, it is necessary to effectively control the congestion problem of sensor network to avoid network congestion or relieve the congestion in time. When designing congestion control mechanism of sensor networks, we must consider the following aspects: first, energy efficiency, sensor node capacity is limited, so the design should be simple and the control packet should be small. Second, timeliness, some sensor networks need to do fast response, detection data must be processed in time, such as forest fire detection. Third, the application accuracy, some networks must do certain detection accuracy, so to ensure the throughput of the network. Fourth, fairness. For nodes far away from sink nodes, reasonable packet loss strategy must be designed to ensure the fairness of the network. Generally speaking, congestion control mechanism in sensor networks mainly includes the following three stages: congestion detection, congestion avoidance and congestion relief. As shown in the figure, this paper briefly describes the control methods used in each stage of the congestion process of sensor networks, as follows.
Fig. 5 optimization of congestion control mechanism in Clustered Sensor Networks

Congestion detection of clustered sensor network is to judge whether the sensor network is running smoothly, when congestion will occur or whether there is a trend of congestion according to the running state of the network. It is the basis of congestion control of clustered sensor network. The timeliness and accuracy of congestion detection seriously affect the performance of congestion control. Only through accurate detection can we take relevant measures in time to make effective adjustment. Based on the above figure, the optimization steps of congestion control mechanism in Clustered Sensor Networks can be adjusted and improved to better ensure the research requirements of effective control of network congestion.

3. Analysis of experimental results

A simulation experiment is carried out to verify the effectiveness of cluster sensor network congestion control method based on T-S fuzzy model. The model includes one coordinator node and ten routing nodes. The queue length in the node is controlled at 20 packets, and the maximum number of data retransmission is 7. The initial energy of a single cluster sensor node is 0.75j. The initial value of the end-to-end notification window is 1, the slow start threshold is 4, and the congestion window is 24. The node queue length is:

$$\gamma = 2; \alpha = 1.4; p_0 = 0.005; \mu_0 = 0.015; q_0 = 20; w_0 = 18.$$

The maximum data generation rate of the node is 25kbit / s, the transmission time of the node occupying the channel is 157 symbols (2512 μs), the maximum backoff times of the node in the channel is 10, and each fixed backoff time is 20 symbols. Other parameters are set according to IEEE802.15.4 standard. In order to simulate the real network space model, n sensor network nodes are randomly deployed in the network monitoring area. In order to analyze and study the performance of ct-s fuzzy model, the initial energy of the network node and the ability of sending and receiving data are fixed, and the position of the network node in the network is fixed. Based on this, the topological structure of clustered sensor network nodes is collected and analyzed, as shown in the following figure:
As shown in the figure, the topological structure of a network node used in the simulation, the network space scale is 200m × 200m, including 199 network nodes and 1 sink node. The pentagram icon in the network center is sink sink node, and the coordinates are (0, 0). It is an effective method to test the performance of cooperative path congestion control algorithm through software simulation experiment. Through comparative simulation, we can intuitively see the ability of three congestion control algorithms to deal with network congestion under the same conditions. In recent years, OPNET, NS2 and MATLAB are popular network routing protocol simulation software. Considering the powerful function of B, the software is used for simulation, and the visual graph is obtained for comparative analysis of network routing protocol performance. In order to test the effectiveness of the proposed control method, the random selection of nodes in Clustered Sensor Networks is tested. The figure below shows the change of the queue in the node within 200 seconds. Where $q_1(t)$ is considering the congestion of adjacent nodes, $q_2(t)$ is not considering the congestion of adjacent nodes.
It can be seen from the test that when considering the congestion of neighboring nodes, the fluctuation of queue length is smaller and the system is more stable. The main reason is that when considering the communication state of neighboring nodes, when the current node is congested and the neighboring node is not congested, it can be considered that the node congestion can be completed by its own adjustment in a short time, and it does not need to reduce the window size to reduce the amount of data transmission, so the data within the node is relatively less volatile and basically remains unchanged, while for the node without considering the congestion of neighboring nodes The probability of channel being marked is random and oscillatory. The main reason is that when considering the communication state of adjacent nodes, when the current node is congested and the adjacent nodes are not congested, the communication channel can not be congested and not marked. Therefore, the probability of channel being marked is relatively stable, and the probability of channel being marked without considering the communication state of adjacent nodes is more affected by the network state. The amount of data received by large-scale network changes with time as shown in the figure. The throughput of network nodes changes with time, and the throughput at the corresponding time is positively correlated with the amount of network data, so the amount of data is bound to change. The abscissa is the number of network cycles, and the ordinate is the amount of data received by the network. All the sensor nodes in the network send data once for a round. When the network runs to a certain stage, most of the energy of the network nodes is exhausted, and the node failure is called dead node. The amount of data received by the network tends to be stable. Furthermore, the changes of the amount of data received by the network over time are compared and analyzed. The specific results are shown in the following figure.
As can be seen from the figure, with the increase of time, the growth rate of data received by the network with traditional arc control is not obvious, the network congestion occurs, and the throughput decreases. After calculation, the amount of data received by ccama control network is about 1.56 times of that received by arc control network, and the amount of data received by T-S fuzzy model control network is about 32.2% higher than that received by ccama control network. Therefore, in small-scale cases, T-S fuzzy model control network congestion phase throughput is greater than ccama and arc control network congestion, T-S fuzzy model is more conducive to control network congestion. Sensor congestion will lead to network data transmission delay, the abscissa is the number of cycles, the ordinate is the network delay time. In the case of network congestion caused by excessive network load, the number of network packet loss and retransmission will continue, and the network delay will continue to increase. Therefore, different congestion control algorithms are adopted to alleviate congestion and reduce network delay, as shown in the figure below.

Fig. 8 variation of the amount of data received with time
As shown in the figure, the network delay of ccama control network is 22 times less than that of arc control network. The network delay of T-S fuzzy model control network is 42.1% less than that of arc control network, and the network delay of T-S fuzzy model control network is 25% less than that of ccama control network. Therefore, under the condition of small scale, T-S fuzzy model is superior to ccama and arc in reducing network delay, which can alleviate network congestion and improve network performance.

4. Conclusions
With the development and application of clustering sensor network, congestion control has become one of the important research directions of large-scale clustering sensor network applications. For the monitoring of important emergencies, it is necessary to avoid or remove local congestion in time in order to transmit event data in real time and reliably; for the periodic data collection in the sensing area, congestion control should ensure the fairness of node transmission. Although the congestion control of clustering sensor networks has been studied deeply in recent years, the proposed congestion detection, congestion avoidance and congestion relief mechanisms are still far away from the practical application. The simple and accurate congestion detection, timely and efficient congestion notification and distributed adaptive congestion relief mechanisms need further research.

Reference
[1] Hwang S, Kim H S. Extended Disturbance Observer-based Integral Sliding Mode Control for Nonlinear System via T–S Fuzzy Model[J]. IEEE Access, 2020, PP(99):1-1.
[2] Ren C, He S, Luan X, et al. Finite-Time L-Gain Asynchronous Control for Continuous-Time Positive Hidden Markov Jump Systems via T-S Fuzzy Model Approach[J]. IEEE Transactions on Cybernetics, 2020, PP(99):1-11.
[3] Jianzhong Z, Yang Z, Yanhe X, et al. A Heuristic T-S Fuzzy Model for the Pumped-Storage
Generator-Motor Using Variable-Length Tree-Seed Algorithm-Based Competitive Agglomeration[J]. Energies, 2018, 11(4):944.

[4] Shah D, Mehta A, Patel K, et al. Event-Triggered Discrete Higher-Order SMC for Networked Control System Having Network Irregularities[J]. IEEE Transactions on Industrial Informatics, 2020, 16(11):6837-6847.

[5] Ma L, Liu X, Wang H, et al. Congestion Tracking Control for Multi-Router TCP/AQM Network Based on Integral Backstepping[J]. Computer Networks, 2020, 175(11):107278.

[6] Karunathilake H, Hewage K, Prabatha T, et al. Project deployment strategies for community renewable energy: A dynamic multi-period planning approach[J]. Renewable energy, 2020, 152(Jun.):237-258.

[7] Wang N, Pedrycz W, Yao W, et al. Disjunctive Fuzzy Neural Networks: A New Splitting-Based Approach to Designing T-S Fuzzy Model[J]. IEEE Transactions on Fuzzy Systems, 2020, PP(99):1-1.

[8] Chen J, Li J, Zhao W. T-S fuzzy model-based adaptive repetitive consensus control for multi-agent systems with imprecise communication topology structure[J]. International Journal of Systems Science, 2019, 50(5-8):1-12.

[9] Jin Z, Zhao Q, Su Y. RCAR: A Reinforcement-Learning-Based Routing Protocol for Congestion-Avoided Underwater Acoustic Sensor Networks[J]. IEEE sensors journal, 2019, 19(22):10881-10891.

[10] Nannan R, Zhanshan W, Huaguang Z. Finite-time Stabilization for Discontinuous Interconnected Delayed Systems via Interval Type-2 T-S Fuzzy Model Approach[J]. IEEE Transactions on Fuzzy Systems, 2018, PP(2):1-1.

[11] Chen J, Li J, Duan R. T-S fuzzy model-based adaptive repetitive consensus control for second-order multi-agent systems with imprecise communication topology structure[J]. Neurocomputing, 2018, 331(FEB.28):176-188.

[12] Vu V P, Wang W J, Chen H C, et al. Unknown Input Based Observer Synthesis for a Polynomial T-S Fuzzy Model System with Uncertainties[J]. IEEE Transactions on Fuzzy Systems, 2018, 26(3):1447-1458.

[13] Satoh D, Takano Y, Sudo R, et al. Reduction of Communication Demand under Disaster Congestion using Control to Change Human Communication Behavior without Direct Restriction[J]. Computer Networks, 2018, 134(APR.7):105-115.

[14] Zhang N, Xue X, Xia X, et al. Robust T-S fuzzy model identification approach based on FCRM algorithm and L1-norm loss function[J]. IEEE Access, 2020, PP(99):1-1.

[15] Zhou K, Huang T, Zhao T, et al. Membership-Function-Dependent Stability and Stabilization Conditions for T-S Fuzzy Time-Delay Systems[J]. IETE Journal of Research, 2019, 65(3):351-364.

[16] Jaghargh M J P, Mashhadi H R. Structural and behavioural evaluation of renewable energy power plants' impacts on transmission network congestion using an analytical approach[J]. IET Renewable Power Generation, 2020, 14(7):1164-1173.

[17] Cheng J, Huang W, Lam H K, et al. Fuzzy-Model-Based Control for Singularly Perturbed Systems with Nonhomogeneous Markov Switching: A Dropout Compensation Strategy[J]. IEEE Transactions on Fuzzy Systems, 2020, PP(99):1-1.

[18] Zhang L, Lu J, Long M, et al. A Cascading Failures Perspective Based Mesoscopic Reliability Model of Weighted Public Transit Network considering Congestion Effect and User Equilibrium Evacuation[J]. Mathematical Problems in Engineering, 2018, 28(P.T.5):1-13.

[19] Wang G, You D, Zhang Z, et al. Network-Constrained Unit Commitment Based on Reserve Models Fully Considering the Stochastic Characteristics of Wind Power[J]. Energies, 2018, 11(2):435-438.

[20] Zhang G, Jia H, Yang L, et al. Research on a Model of Node and Path Selection for Traffic Network Congestion Evacuation Based on Complex Network Theory[J]. IEEE Access, 2019, 8(10):7506-7517.