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Study on Communication Service Strategy for Congestion Issue in Smart Substation Communication Network

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ABSTRACT Shared networks can improve the efficiency of smart substation communication infrastructure, but they pose challenges for the real-time performance and reliability of communication. By analyzing the traffic rate and causes of congestion in a substation environment, we propose a communication service strategy using a message information label to manage the congestion issues. This strategy implements fast identification and filtering of messages by condensing key information into a message label at intelligent electronic devices and checking it along with traffic rates at switches. We put forward a communication scheduling method called distributive length WRR_LLQ that adapts to the different characteristics and real-time demand of various message types. OPNET simulation results show that the strategy successfully identifies and discards disguised error messages with high traffic rates, avoids timeouts and packet drops in the transmission process of important messages when congestion occurs, and reduces the transmission time of other messages.

INDEX TERMS Smart substation, quality of service, communication scheduling, real-time performance, reliability.

I. INTRODUCTION

Smart substations are critical for the construction and support of the smart grid. In recent years, the promulgation of the IEC61850 communication protocol and the development of intelligent electronic devices (IEDs), industrial switches, and Ethernet technology provides a broader means of data exchange between devices in smart substation [1], [2].

The communication network is key to the realization of substation functions, such as relay protection and monitoring. The real-time performance and reliability of the communication network directly determines the availability of the smart substation [3]–[5]. With the progress of communication technology, researchers have begun to study the scheme of a shared network connecting all of IEDs into a single network. Although this shared network approach can improve the efficiency of the network, it also poses challenges for the real-time performance and reliability of communication [6], [7].

When faults or network attacks occur in a substation, many unexpected messages and error messages appear on the network. These messages accumulate at the switch and cause network congestion. In turn, the congestion causes timeouts and dropped packets, including important SV (Sampling Value) and GOOSE (Generic Object Oriented Substation Event) messages, which seriously affect the safe operation of the smart substation [8], [9].

At present, general switching technology, such as PQ (Priority Queue) and VLANs (Virtual Local Area Network) are being introduced to smart substations [10]–[13]. VLAN technology uses VLAN identity to limit the transmission of message to a certain range. The scheduling methods based on PQ or WRR (Weighted Round Robin) usually ensure transmission for important messages (e.g. GOOSE and SV messages) by giving them high priority or weight. However, each type of message within a smart substation has specific characteristics with widely different requirements for communication performance, and the general scheduling methods are unable to allocate resources for each type of message efficiently [13]. Moreover, if error messages are disguised as important messages, error messages will still affect the transmission of other important messages.

In this paper, we introduce the types and characteristics of messages in a smart substation communication network,

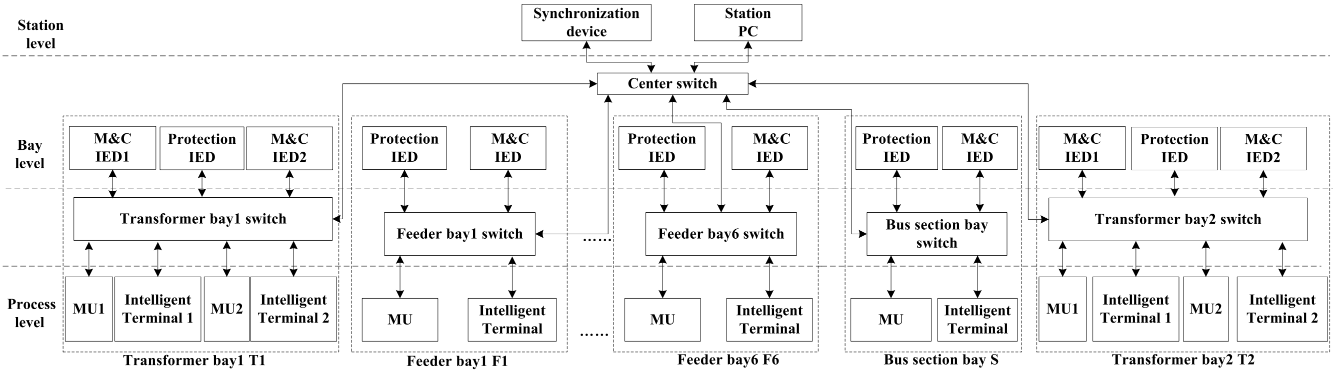


FIGURE 1. The topology of a sample smart substation communication network.

and describe the composition of the message transmission time. We then analyze the possible congestion problem in the network. According to the DiffServ (Differentiated Service) model of QoS (Quality of Service), we put forward a communication service strategy based on the message information label. This service strategy implements type identification and filtering for message using message information labels and traffic rate monitoring. The strategy allocates resources for messages according to their message types through a communication scheduling method using distributive length WRR_LLQ (DL WRR_LLQ). This strategy avoids the time-outs and dropped packets relating to important messages when congestion occurs by identifying and discarding heavy data flows of disguised error messages. The strategy improves the delay characteristics of secondary messages while ensuring the real-time performance of important messages.

II. THE TYPE OF MESSAGE IN THE COMMUNICATION NETWORK OF SMART SUBSTATION

The messages transmitted within a smart substation communication network include SV messages, GOOSE messages, MMS (Manufacturing Message Specification) messages and SNTP (Simple Network Time Protocol) messages [14]–[16]. IEC61850 classifies SV messages as type 4 - original data messages, GOOSE messages as type 1 - fast messages, SNTP messages as type 6 - time synchronization messages, and MMS messages as types 2, 3, and 5 (medium-speed messages, low-speed messages, and file transfer messages, according to the different functions). The communication performance requirements of the various messages are given in Table 1 [17].

GOOSE messages transmit control and status data. SV messages transmit sampling data from a merging unit (MU). MMS messages transmit state data, report data, fixed value data, documents, and control data from a distance. SNTP messages synchronize times between IEDs [18]–[20]. A representative 220 kV smart substation (D2 - type 1) contains nine bays (transformer bays T1, T2, feeder bays F1–F6, and bus section bay S). All the IEDs are connected within the same network. A bay switch connects all IEDs in the bay. The network uses a center switch to connect the bay switches in a star topology. The topology of this sample smart substation communication network is shown in Fig. 1.

TABLE 1. The performance requirements of messages.

Message type	Transmission-time requirement	Packet drop rate requirement
GOOSE	< 3 ms	No drop
SV	< 3 ms	No drop
MMS-medium-speed	< 100 ms	No drop
MMS-low-speed	< 500 ms	retransmission
MMS-file transfer	No specific restriction	retransmission
SNTP	< 1 s	No drop

Merge units and intelligent terminals are process-level devices, while protection IEDs and measurement and control IEDs (M&C IEDs) are bay-level devices. The station PC and synchronization device are station-level devices. Within the network, MUs broadcast SV messages, GOOSE messages are transmitted between bay-level and process-level devices. MMS messages flow between bay-level devices and station-level devices. SNTP messages are transmitted between the synchronization device and other devices.

III. ANALYSIS OF TRAFFIC RATE AND CONGESTION ISSUES IN A SMART SUBSTATION COMMUNICATION NETWORK

A. THE ANALYSIS OF TRAFFIC RATE

According to IEC61850, SV and GOOSE messages use the ASN.1 (Abstract Syntax Notation One) grammar to define an APDU (application layer protocol data unit).To transmit the SV-PDU and GOOSE-PDU with an ISO/IEC8802-3 standard Ethernet data frame (sometimes referred to simply as a "data frame"), IEC61850 places an APDU in the application data field of a data frame. The length of the data frame for an APDU is as follows:

$$L_{\mathrm{p}} = L_{\mathrm{APDU}} + L_{\mathrm{FH}} + L_{\mathrm{FCS}} \tag{1}$$

In the formula, L_{APDU} is the length of APDU with the unit byte, L_{FH} is the length of the frame header, and L_{FCS} is the length of the frame check sequence.

TABLE 2. The approximate traffic rates of a single data flow of messages.

Message type	Normal traffic rate	Maximum traffic rate
SV	33 Mbps	33 Mbps
GOOSE	0.0025 Mbps	1.3 Mbps
MMS-medium-speed	0.01 Mbps	1.65 Mbps
MMS-low-speed	0 Mbps	1.86 Mbps
MMS-file transfer	0 Mbps	1 Mbps
SNTP	0.0001 Mbps	0.0001 Mbps

Because SV and GOOSE messages are transmitted using identical data frames, the L_{FH} and L_{FCS} of both are the same. L_{FH} is 26 bytes: 6 bytes for destination address, 6 bytes for source address, 4 bytes for priority tag, 2 bytes for Ethernet type, 2 bytes for application identifier (APPID), 2 bytes for frame length, 4 bytes reserved. L_{FCS} is 4 bytes.

According to IEC61850-8-1, a GOOSE-PDU message is 130–280 bytes long, so the L_{p} of a GOOSE message is 160–310 bytes. IEC61850-9-2 specifies the length of an SV-PDU message as 160–310 bytes, so the L_{p} of an SV message is 190–340 bytes [11], [17]. MMS messages typically are transmitted by ISO/IEC8802-3 standard Ethernet data frame with TCP/IP with a maximum length of 1480 bytes [11], [13].

In a smart substation communication network, each data flow carries only one type of message, Table 2 presents the approximate traffic rate for each flow [11], [13], [17].

The sending frequency of SV messages is usually 4000 Hz or 12000 Hz. The maximum length of an SV message is about 340 bytes. The shortest arrival interval of SV messages is 0.000083 s for a sending frequency of 12000 Hz. Thus, the maximum traffic rate of SV messages is about 33 Mbps (340 bytes × 8 × 12000 Hz ≈ 33 Mbps). The maximum length of a GOOSE message is about 310 bytes with a minimum arrival interval of 0.002s (when an emergent event occurs) [7]. Thus, the maximum traffic rate of GOOSE messages is about 1.3 Mbps (310 bytes × 8 / 0.002 s ≈ 1.3 Mbps). The maximum length of an SNTP message is about 100 bytes with a shortest arrival interval of 1 s, yielding a maximum traffic rate of about 100 bps [20]. The length range of MMS messages is not fixed, and sometimes, continuous MMS messages are transferring file information with a length of 1480 bytes each. Most MMS messages, however, are medium-speed MMS messages transmitting state report data, with a traffic rate that is far less than that of SV messages. When an event such as a file transfer occurs, the traffic rate of MMS messages will rise quickly in a short time [12], [17].

B. THE COMPOSITION OF TRANSMISSION TIME

IEC61850-5 defines the message transmission time T_{trans} as the time between the sender (source node) placing data onto the transmission stack and the receiver (destination node) removing the data from the transmission stack. This time consists of frame sending time T_{frame}, propagation time T_{prop}, waiting time T_{wait}, forwarding process time $T_{\mathrm{processor\_f}}$, and receiving process time $T_{\mathrm{processor\_r}}$. The frame sending time is determined by the message length and network data rate. The receiving process and forwarding process times are determined by the performance of the node. The propagation time is determined by transmission medium and transmission distance. The waiting time is determined by the network status.

If a message from a source node to a destination node passes X nodes (the first node is the source node, and the Xth node is destination node, $X > 1$), the message transmission time is as follows:

$$T_{\mathrm{trans}} = 8(X-1)\frac{L}{R} + \sum_{x=2}^{X-1}\left(T^{x}_{\mathrm{wait}} + T^{x}_{\mathrm{processor\_f}}\right) + \frac{D}{V} + T_{\mathrm{processor\_r}} \tag{2}$$

where $T_{\mathrm{processor\_r}}$ is the processing time of the destination node in seconds (all times are given in seconds in this paper); $T^{x}_{\mathrm{processor\_f}}$ is the processing time of the xth node; T^{x}_{wait} is the waiting time of the xth node; L is the length of the message in bytes; R is the network data rate in bps; D is the total transmission distance in meters; and V is the signal speed in m/s.

In a smart substation communication network with a star topology, a message will go through at most three switches to reach the destination node. Assuming a maximum message length of 1480 bytes, such a network has a forwarding process time on the switch of about 0.002 ms and a receiving process time of about 0.0003 ms. The total propagation distance is generally within 1 km at a speed of 200 m/μs. Typically, these networks use a data rate of 100 Mbps or 1000 Mbps. Without considering the waiting time, the maximum transmission time of a message is about 0.4873 ms on a 100 Mbps network according to formula (2). At 1000 Mbps, the maximum transmission time of a message is about 0.0589 ms. Under normal operating conditions and without waits, these transmission times meet the performance requirements.

Because the sending of MMS message is random, the network status are indeterminate, thus the waiting time is not fixed. When a burst of messages arrives at a forwarding port, they will accumulate in a waiting queue. For a typical FIFO (First In First Out) queue, the waiting time T^{k}_{wait} of a message k at the port is as follows:

$$T^{k}_{\mathrm{wait}} = \frac{8\left(\sum_{i} L_i + L_{\mathrm{r}}\right)}{R} \tag{3}$$

where L_i is the length of other messages waiting in front of message k in the queue, and L_r is the length of the remainder of the message currently being sent.

C. THE ANALYSIS OF CONGESTION ISSUE

The rate of data arriving at a switch forwarding port S in bps (for sending) is equal to the sum of all data flows through the port. When the rate of data arriving at the port exceeds the sending data rate of the port (usually equal to the network data rate) because of a fault or network attack, data accumulates

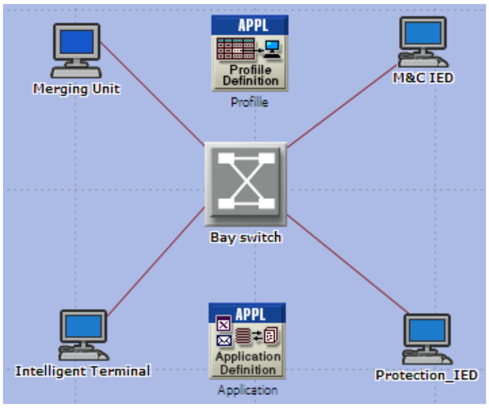


FIGURE 2. The topology of feeder bay network.

in the switch's queue and leads to congestion. The number of messages in the waiting queue increases along with the waiting time for a message at the end of the queue according to formula (3). When the waiting queue is full, the switch discards additional incoming messages, a behavior known as packet drop.

Fig. 2 shows a simulation model of an example feeder bay network. The network data rate is 100 Mbps, and the switch uses a FIFO queue with a maximum length of 100 packets. SV messages coming from the MU have a length of 200 bytes and a sending frequency of 4000 Hz. The traffic rate of GOOSE messages is 0.8 Mbps. With a message length of 200 bytes, GOOSE messages travel from the intelligent terminal to the protection IED and to the measurement and control IED.

Between 90 and 110 s after the start of the simulation, the measurement and control IED begins sending broadcast error messages with a length of 1400 bytes and frequency of 12000 Hz. Under these conditions, the measured transmission time and packet drop rate of SV and GOOSE messages is shown in Fig. 3.

It can be seen from the Fig. 3 that when error messages occur, the transmission time of SV and GOOSE messages increases sharply and no longer meets the requirements of IEC61850. Furthermore, packet dropping occurs because the data rate of messages arriving at the port (141.6 Mbps) exceeds the network data rate (100 Mbps).

The data flow at the forwarding port on the central switch connected to the switch in the bus section bay is higher than others because the protection IED in the bus section bay must communicate with MUs and intelligent terminals in other bays. Using the example from Fig. 1, the forwarding port on the center switch passes SV messages from 10 MUs and GOOSE messages from 10 intelligent terminals across 8 bays. With data flows of MMS messages, the maximum data rate arriving at this port is approximately 380 Mbps, meaning that this network should use a 1000 Mbps data rate. If the flow of error messages at this port is more than 620 Mbps, congestion will occur even at 1000 Mbps.

Timeouts and packet drops in the transmission of important messages leads to abnormal operation of a substation, which may lead to power failure [11].

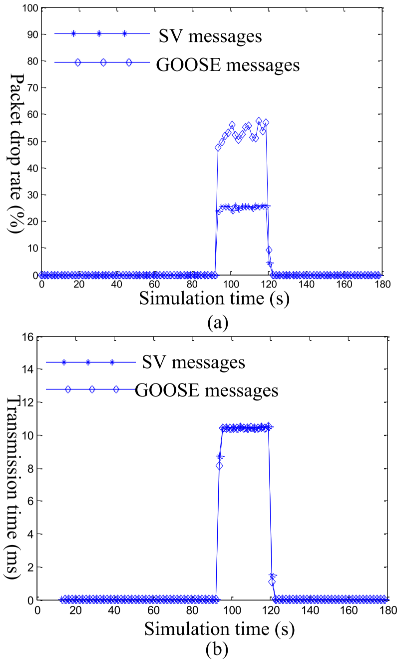


FIGURE 3. Transmission time and packet drop rate of SV and GOOSE messages when error messages occur.

IV. COMMUNICATION SERVICE STRATEGY BASED ON MESSAGE INFORMATION LABEL

The current service strategy ensures real-time performance for important messages by placing them in a high-priority (or weight) queue. The transmission of important messages, however, is still affected by error messages labeled as important messages and placed in the high-priority queue.

A. MESSAGE IDENTIFICATION METHOD BASED ON MESSAGE INFORMATION LABEL AND TRAFFIC RATE MONITORING

Switches in smart substation communication networks generally identify and schedule messages by checking the priority label. Message information useful for further identification is encapsulated in data fields in the APDU, which has a complex encoding. We propose simplifying key message information and placing it into a reserved field. By checking the new message label and monitoring the traffic rate, we achieve fast message identification and quickly discard error messages that affect the transmission of important messages.

Fig. 4 shows the location and structure of our message information label in the ISO/IEC8802-3 standard Ethernet data frame. The information needed for message identification includes source device, message type, message length, arrival interval, and the traffic rate of messages in one data flow. IEDs construct the information label and place it into the reserved field. Switches check the information label, obtain the message length and arrival interval, monitor the traffic rate, and determine whether a message is normal.

Table 3 shows the relationship between source devices and message types (with each code).

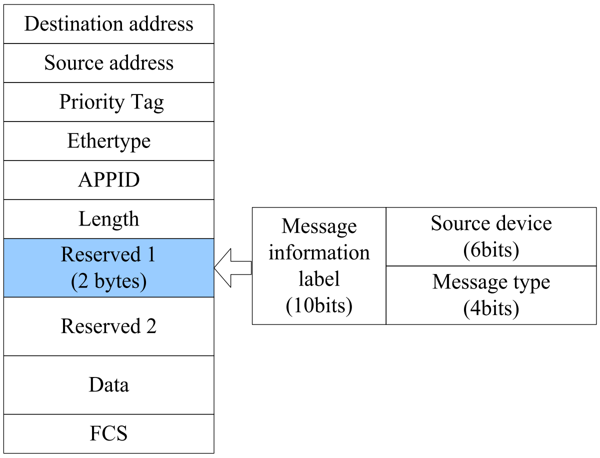


FIGURE 4. The location and structure of the proposed message information label in the ISO/IEC 8802-3 standard Ethernet data frame.

TABLE 3. The relationship between source devices and message types (with each code).

Source device	Message type
Merge Units(000000)	SV (0001)
Intelligent Terminals(000001) Merge Units(000000) Protection IEDs(010000) M&C IEDs(010001)	GOOSE(0010)
Bay level devices Station PC(100000)	MMS-medium speed (0100) MMS-low speed (0101) MMS-file transfer (0110)
Synchron device(100001) All other device	SNTP(0011)

When a message arrives at the receiving port of a bay switch, the switch will first check its source device determined by the receiving port. (A receiving port of a bay switch is connected with only one IED in an operating substation.) If the determined IED does not match the source device given in the information label of the message, then the source type will be judged as erroneous. Note that the center switch is not responsible for checking the source type. After checking the source type, the switch will check that the message type is appropriate for the source device.

According to the previous analysis, each type of message has its own flow characteristics. Error messages usually are long and arrive quickly in large numbers. Thus, they easily cause congestion. Switch will also check that the message type is appropriate for the flow characteristics, which include the message length, arrival interval and traffic rate.

For SV, GOOSE, and SNTP messages, we treat a flow as abnormal when the message length is more than twice the maximum length (message length abnormal), the arrival interval is less than half the shortest arrival interval (arrival interval abnormal), or the traffic rate is more than twice the maximum rate (traffic rate abnormal). We treat a flow as an error when the message length exceeds four times the maximum length (message length error), the arrival interval is less than one-quarter of the shortest arrival interval (arrival interval error), or the traffic rate is more than four times the maximum flow rate (traffic rate error). We treat the traffic rate of MMS messages as abnormal if it is more than 50 Mbps and as an error if the situation lasts for more than 2 s.

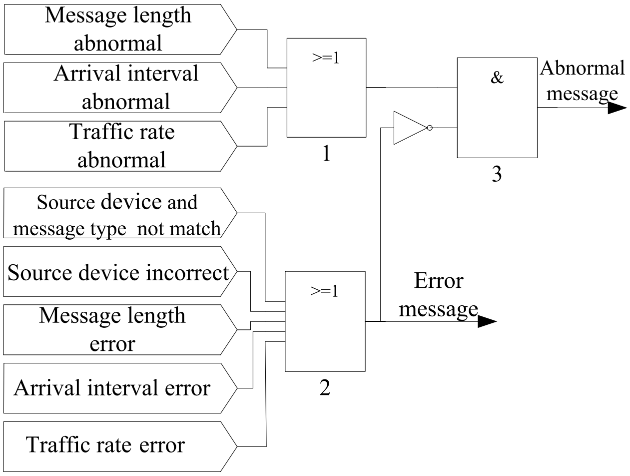


FIGURE 5. The logic diagram for determining whether a message is abnormal or an error.

We determine a message to be an error in any of the following circumstances: the source device and message type do not match, the source device is incorrect, the message length is error, the arrival interval is error, or the traffic rate is error. If a message is not classified as an error, we determine it to be abnormal when the message length is abnormal, the arrival interval is abnormal, or the flow rate is abnormal. Fig. 5 provides a logic diagram of our strategy.

Switches will discard error messages and place abnormal messages in the low-priority queue. For higher level application-related needs (e.g. security or anomaly/attack detection), switches also need to store the statistical data of messages (include the statistical data of error and abnormal messages) in their internal storage and send error messages to a network monitoring device.

B. COMMUNICATION SCHEDULING METHOD BASED ON DISTRIBUTIVE LENGTH WRR_LLQ

To meet the performance requirements for each message type, smart substations usually adopt a PQ (Priority Queue) or WRR (Weighted Round Robin) algorithm [13], [17]. The PQ algorithm processes the high-priority queue preferentially and processes the low-priority queue only when the high-priority queue is empty. When an emergency occurs and the traffic rate increases, the low-priority queues may not be processed in a timely manner.

The WRR algorithm creates N polling queues within the cache of the forwarding port and distributes weights ($W_1 \sim W_N$) for each queue. A single round of polling is divided into T rounds of subsidiary polling ($T = \text{Max}\ (W_i)$). The switches send one message at most from each queue in one round of subsidiary polling. The messages in the queue with the weight of W_i can be sent consecutively in W_i rounds of subsidiary polling. Fig. 6 provides a graphical example of

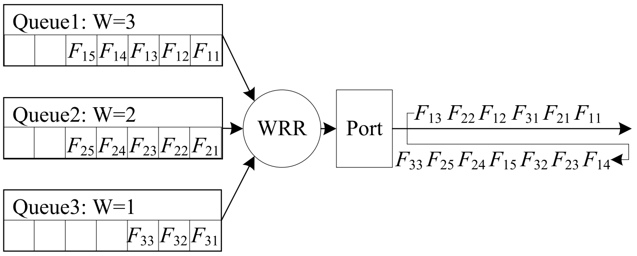


FIGURE 6. An example of the WRR algorithm.

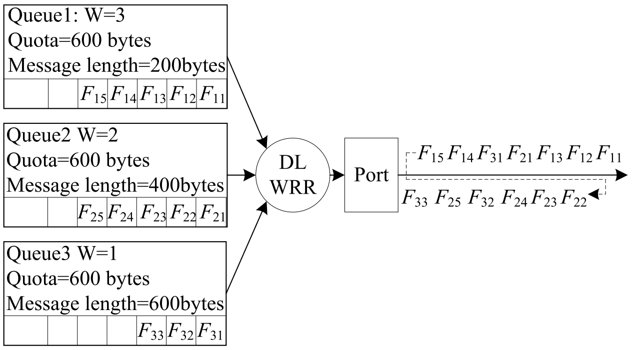


FIGURE 7. An example of DL WRR algorithm.

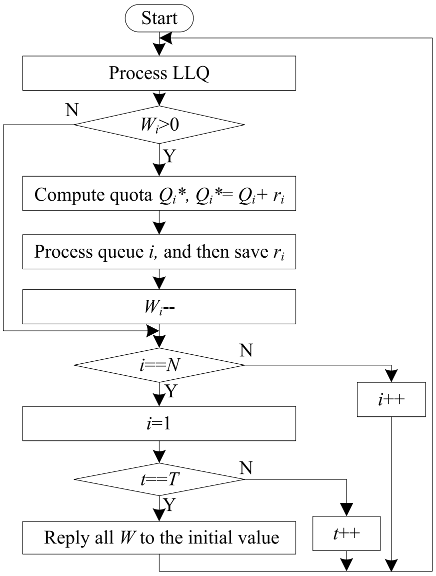


FIGURE 8. The scheduling process using distributive length WRR_LLQ.

the WRR algorithm with three queues. The weights of queues 1, 2, and 3 are set to 3, 2, and 1, respectively. The messages in queue 1 are sent consecutively during three rounds of subsidiary polling.

When there are N nonempty queues, the data rate R_j in bps sent from queue j is as follows:

$$R_j = \frac{RW_jL_j}{\sum_{i=1}^{N} W_iL_i} \tag{4}$$

where L_i is the average message length of queue i, L_j is the average message length of queue j, W_i is the weight of queue i, and W_j is the weight of queue j. This approach means the rate of data that can be sent from the queue with shorter length messages is less than from a queue with longer messages. This is a problem because SV and GOOSE messages are shorter than many MMS and error messages. To solve this problem, we propose a scheduling method called distributive length WRR (DL WRR). This method distributes a sending quota of length Q in bytes for each queue when polled. The total length of messages that can be sent from a queue during a single round of subsidiary polling is shorter than the sending quota allocated to this queue. At the end of the polling round, if the residual quota r is not enough to send the next message in the queue, the residual quota will be saved for use in the next round. The practical quota for one queue in one round of subsidiary polling is Q^* ($Q^* = Q + r$). When the length of a message exceeds Q^*, the entire quota will be saved as residual quota until the new Q^* exceeds the length of this message. Fig. 7 gives a graphical representation of the DL WRR algorithm. The weight of queues 1, 2, and 3 are set to 3, 2, and 1, respectively with a quota of 600 bytes per queue. The length of messages in queues 1, 2, and 3 are 200, 400, and 600 bytes, respectively.

When there are N nonempty queues, the data rate R_j in bps sent from queue j is as follows:

$$R_j = \frac{RW_jQ_j}{\sum_{i=1}^{N} W_iQ_i} \tag{5}$$

where Q_i is the distributed quota length for queue i, Q_j is the distributed quota length for queue j. Under the conditions shown in Fig. 7, the data rate of queue 1 is 0.3 R with the WRR algorithm compared with 0.5 R with the DL WRR algorithm.

To schedule communication more effectively, we put each type of message in a single queue. This allocates resources for messages according to type and minimizes the differences in message length within the same queue. By further adding a LLQ (Low Latency Queue) to the polling, we ensure that the most important messages are forwarded promptly.

Fig. 8 shows the scheduling process using our combined DL WRR_LLQ algorithm. In the diagram, i is the sequence number of polling queue, N is the number of polling queues, t is the sequence number of subsidiary polling rounds, and T is the number of subsidiary polling rounds.

Before processing each polling queue, switches check the LLQ for messages. If so, the switch sends all the messages in the LLQ first. Thus, the maximum waiting time of the first message in the LLQ is as follows:

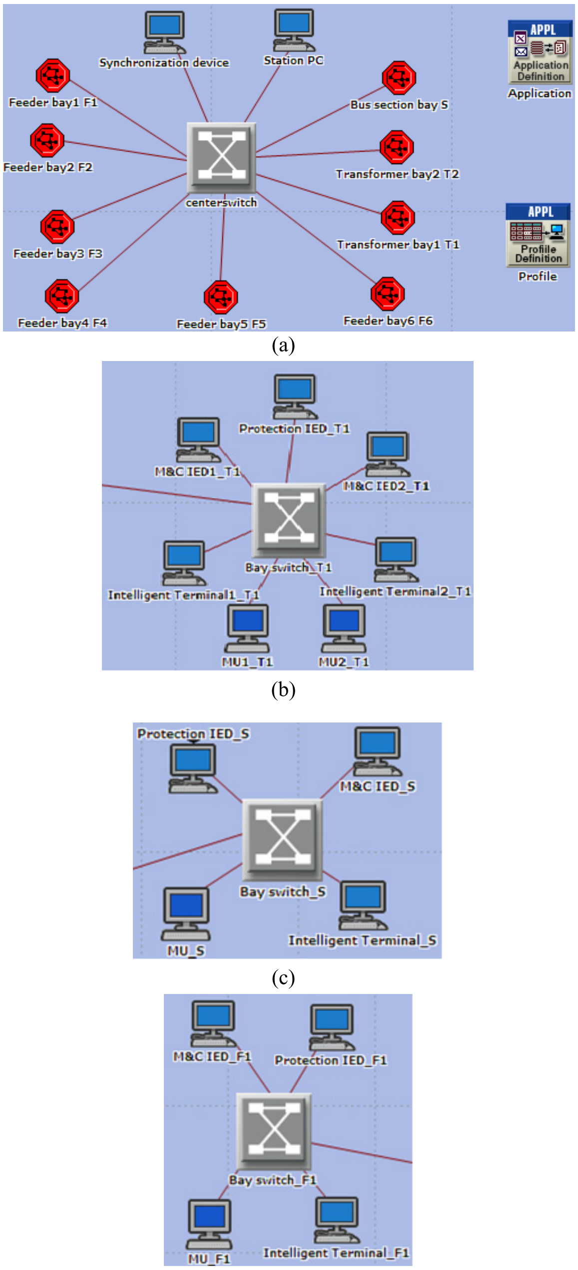
$$\max(T_{\text{waitLLQ}}) = \max[\frac{8(Q_i + L_i)}{R}] \tag{6}$$

where L_i is the length of message in polling queue i, and Q_i is the distributed sending quota length of polling queue i. The LLQ is not one of the polling queues.

The LLQ is suitable for messages of short length, small traffic rate, and high priority. These types of messages ensure

TABLE 4. The characteristics and service queues of messages arriving at the switch forwarding port.

Message type	Message length	Total data rate	Service queue(weight)
GOOSE	300 bytes	1.2 × 10 Mbps	LLQ
SV	300 bytes	28.8 × 10 Mbps	1 (20)
MMS-medium speed	500 bytes	40 × 2 Mbps	2 (6)
MMS-low speed	1000 bytes	40 × 2 Mbps	3 (2)
MMS-file transfer	1480 bytes	40 Mbps	4 (2)
SNTP	100 bytes	0.0001 Mbps	5 (6)
Disguised MMS	1480 bytes	100 × 8 Mbps	6 (1)
Disguised SV	1450 bytes	139 × 4 Mbps	



(a)

(b)

(c)

(d)

FIGURE 9. The simulation model of the network. a) The simulation model of whole network. b) The simulation model of transformerbay1. c) The simulation model of bus section bay. d) The simulation model of feeder bay1.

that the LLQ is frequently empty, leaving the other queues relatively unaffected. To prevent messages in the LLQ from being discarded, the data rate of messages arriving at LLQ is less than the network data rate. To prevent a message in polling queue j from being discarded, R_j must be greater than or equal to S_j, the data rate of messages arriving at queue j.

V. SIMULATION ANALYSIS

According to Table 1, the requirements for transmission time and drop rate of GOOSE and SV messages are the most stringent. With shorter message lengths and smaller traffic rates, GOOSE messages are suitable for the LLQ. The performance requirements of medium-speed MMS messages are more stringent than low-speed messages. The requirements for MMS file transfer messages are the least stringent.

We simulated a network with a 1000 Mbps data rate using the OPNET platform, as shown in Fig. 9.

We choose a forwarding port on the central switch connected to the switch in the bus section bay as our observation subject. Table 4 shows the flow characteristics and service queues of messages arriving at this port.

For testing our service strategy, the traffic rates of MMS messages was set larger than a typical real-life situation. Beginning 85 s from the start of the simulation, eight M&C IEDs in another bay began sending error messages disguised as MMS medium-speed messages by falsifying the message type at a traffic rate of 100 Mbps to the protection IED of the bus section bay. Additionally, four protection IEDs in other bays sent error messages disguised as SV messages (again falsifying the message type) with a traffic rate of 139 Mbps to the protection IED of the bus section bay. Among them were two flows of malformed SV messages indicating an MU as the source device. In the case shown in Table 4, without the use of our identification method, the arriving data flow rate of 1856 Mbps exceeded the sending data rate of 1000 Mbps for the port.

To ensure the real-time and reliable transmission of important messages, we set the weights and quotas of polling queues according to our performance requirements. We created service queues for each type of message (LLQ and polling queues 1∼5) and polling queue 6 for abnormal messages. Weights for queues 1 through 6 were set to 20, 6, 2, 2, 6, and 1, respectively. We gave queue 5 a quota of 200 bytes, and queue 6, 400 bytes. We gave 1500 bytes to the other queues. According to formula (5), the data rate sent from queue 1 (for SV messages) was about 644 Mbps, the data rate from queue 2 (MMS medium speed messages) was about 193 Mbps, and the data rate from queue 5 was about 26 Mbps, all of which met the condition of avoiding packet drop. The data rate for abnormal messages was about 9 Mbps, which is a small part of the total amount.

TABLE 5. The packet drop rate of messages with three identifying methods.

Message type	No method	Label only	Label and flow monitoring
GOOSE	No drop	No drop	No drop
SV	31%	No drop	No drop
MMS-medium speed	76%	74%	No drop
MMS-low speed	32%	No drop	No drop
MMS-file transfer	35%	No drop	No drop
SNTP	No drop	No drop	No drop
Disguised MMS	87%	85%	91%
Disguised SV (no falsified source)	43%	100%	100%
Disguised SV (falsified source)	43%	100%	100%

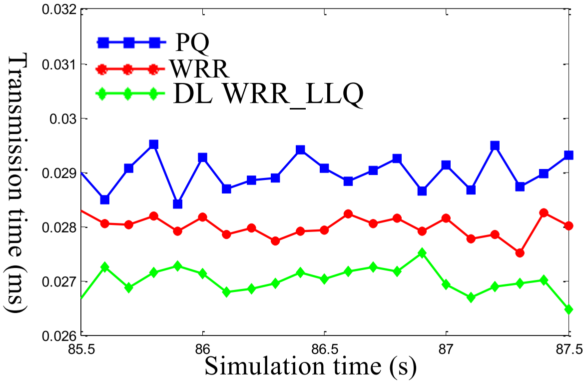


FIGURE 10. Transmission time of medium-speed MMS message.

Table 5 shows the packet drop rates of messages using different identification methods.

Without our message information label, disguised SV and MMS medium-speed messages were put into the corresponding queues and seriously influenced the transmission of normal SV and MMS medium-speed messages and caused packet drops for two types of messages. Using our message information label alone, we discarded the disguised SV messages with a falsified source because of incorrect source device and discarded the disguised SV messages without a falsified source type because of a mismatch between the source device and message type. After combining information label checking with traffic rate monitoring, we put the disguised MMS messages into the abnormal queue because of abnormal traffic rates.

Figs. 10 through 13 summarize the transmission times of the various message types in the presence of error messages for the PQ, WRR, and DL WRR_LLQ scheduling methods after using the proposed identification method.

Figs. 10 through 13 show that when compared with the traditional PQ method, WRR ensures the transmission time of important messages and reduces the transmission time of secondary messages, such as MMS medium- and low-speed messages. Using the LLQ for GOOSE messages reduces their transmission time and has little influence on the transmission time of other messages because of the shorter length and smaller traffic rate. Compared with the WRR method, our DL WRR_LLQ method additionally reduces the message transmission time of SV and MMS medium-speed messages with shorter length. Compare with the strategy using WRR scheduling method and no identification method (referred to simply as "general strategy"), the maximum transmission times of various message types using the proposed service strategy are listed in Table 6.

It can be seen from the Table 6, when congestion occurs, the proposed service strategy can reduces the transmission time of messages.

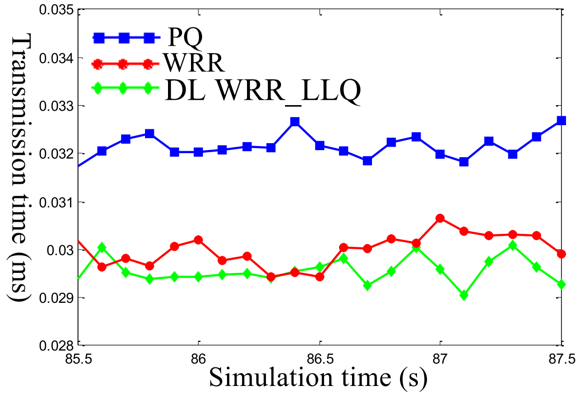


FIGURE 11. Transmission time of low-speed MMS message.

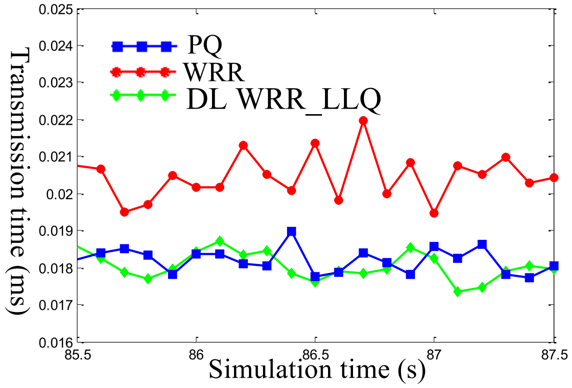


FIGURE 12. Transmission time of GOOSE message.

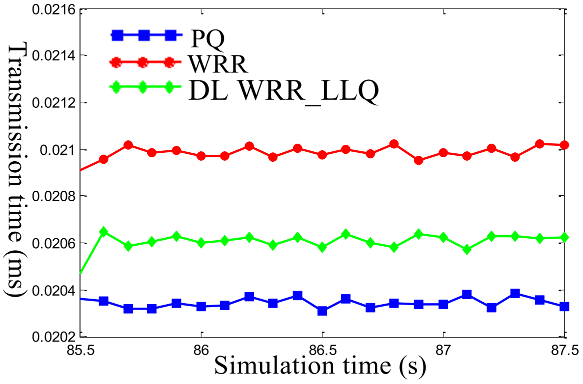


FIGURE 13. Transmission time of SV message.

TABLE 6. The maximum transmission times of messages with general and proposed service strategy.

Maximum Transmission time	General strategy	Proposed strategy
GOOSE	0.0233 ms	0.0187 ms
SV	39.2 ms	0.0207 ms
MMS-medium speed	138 ms	0.0273 ms
MMS-low speed	505 ms	0.0301 ms
MMS-file transfer	228 ms	0.0561 ms
SNTP	0.278 ms	0.0235 ms

VI. CONCLUSION

In this paper, we proposed a communication service strategy to reduce network congestion based on a message information label after analyzing traffic rates, message transmission time, and causes of congestion in a smart substation communication network. This strategy condenses the source device and message type into a message information label and identifies messages by checking the labels and monitoring the traffic rate. The strategy uses a logical strategy for determining and processing abnormal and error messages. Furthermore, we proposed a communication scheduling method based on distributive length WRR_LLQ to manage the network in compliance with the performance requirements for each message type. This strategy tailors queues, queue weights, and queue quotas according to the characteristics of the various messages. Our experiments show that the service strategy can identify and discard disguised error messages effectively and can ensure the reliable real-time transmission of important messages. Our strategy also reduces the transmission time for other messages and improves the real-time performance and reliability of communication in smart substation communication networks.

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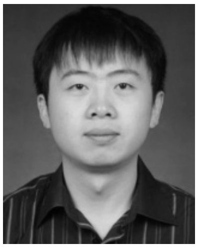

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