SCD based IEC 61850 Traffic Estimation for Substation Automation Networks

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***Abstract*—In Substation Automation System(SAS), communication network plays a critical role in the real time operation of the substation. IEC 61850 is a communication standard for SAS for the data transmission within and between station level, bay level and process level. The standard defines both the information model and the services used for communication between Intelligent Electronic Devices (IEDs) in a substation. The information model can be mapped to application protocols like MMS, GOOSE, SV of which GOOSE and SV messages are time critical and use Layer 2 of Open Systems Interconnection (OSI) model. IEC 61850 also defines substation configuration description (SCD), which embodies the substation model, the IED equipment model and the communication network model. With the increase in size and complexity of SAS network, it is desirable to properly segment multicast flows in order to avoid overloading at IEDs with unsubscribed messages. Knowledge of data flows and traffic patterns allow detecting network bottlenecks and aid in systematic network segmentation, filtering and segregation of the traffic. Hence there is a need to optimize the traffic segmentation and generate appropriate traffic filters which will be configured in network switch. Furthermore, by analyzing the application data and logical dataflow information present in the SCD file, it is possible to estimate the network bandwidth and flow latency. This would validate the network configuration for the fulfillment of the performance requirements based on the dataflow information in SCD file. So, there is a need to develop models that will estimate the GOOSE/SV traffic from the SCD file data. This paper proposes a method to optimally segment the Layer 2 network traffic and also a model to estimate GOOSE/SV traffic in SAS Network based on the information extracted from SCD file. This estimation would aid in analyzing the required network performance during the deployment and also better planning of SAS networks.**

***Index Terms*—GOOSE message; SV message; Bandwidth estimation; Steady state; Burst mode; Min time; Max time; Sampling rate; Segmented network; Traffic model; Latency model**

I. INTRODUCTION

A Substation Automation System (SAS) is to protect, supervise and control a substation equipment. It comprises full station and bay protection as well as control, monitoring and communication functions and offers safe and reliable operation of the substation. IEC 61850 standard specifies complete communication architecture for station and process bus to ensure a high level of device interoperability. The IEC 61850 document is organized into ten main parts. Among which, IEC 61850-8-1 specifies the Manufacturing Message Specification (MMS) traffic which operates as a client-server protocol, and optionally provide real-time communication mechanisms. IEC 61850-8-1 also defines Generic Object Oriented Substation Events (GOOSE) traffic. GOOSE protocol allows multicast messages across LAN that are communicated horizontally between bays or vertically between process level and bay level. GOOSE messages mainly carry monitoring and control functions, tripping and interlocking information in binary form. IEC 61850-9-2 defines the Sampled Values (SV) traffic which carries voltage and current digital samples. This traffic flows normally over process bus but can also flow over station bus, particularly for bus bar protection and phasor measurement.

IEC 61850 standard provides definite data models and communication services which are the key to interoperability between multivendor substation protection and control devices and gateways via Ethernet. IEC 61850-6 defines substation configuration description language (SCL), which can describe functions of IED, structures of substation and its communication network based on extensive markup language (XML). SCL represents SAS in a unique way with the model description based on IEC 61850. Analyses and comparison of different SCL files are studied in [1] and it further discusses on rules of SCL files in an actual substation project.

The traffic flow calculation algorithm is proposed in [2] by developing a port connection model, a traffic-flow source model, and a traffic-flow service model of SAS communication network. In [3], three types of theoretical models for the data flow in SCN, which are cyclic data flow, stochastic data flow, and burst data flow are proposed. Based on these models, a quantitative analysis of typical data flow is carried out, and the real-time performance for a VLAN-based substation is evaluated. Ubiratan Carmo et al. presented modeling of GOOSE traffic that may benefit engineers in planning the capacity of the SAS and ensuring their scalability throughout their lifetime [4]. The paper also highlights task oriented network segmenting as one of the measures for achieving the guaranteed delay performance of SV messages. Process Bus Implementation on IEDs [5] discusses about the influence of SV messages on IEDs. It considers interpolation algorithms that are used for re-sampling and for lost SV estimation. Challenges in modeling and analysis of SAS network traffic from the data generating mechanism to the transmission and

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retransmission mechanisms are exploited in [6] and it reveals the symbiosis of short range dependence and self-similarity.

This paper discusses the methods proposed for GOOSE/SV traffic segmentation and estimation based on SCD file data. The methods are implemented in .NET 4.5 platform using IEC 61850 libraries. Tool takes SCD file as an input file and provides the traffic estimation for segmented and unsegmented network. The main contributions of this paper are:

- A method for optimization of Layer 2 traffic segmentation based on the logical flows mentioned in the SCD file is proposed along with the method for generating VLAN and multicast filters for all the IEDs in the network post segmentation.
- Model for GOOSE/SV traffic estimation in station and process bus based on the message byte size and transmission mechanism related information mentioned in the SCD file is built.
- Flow latency model is developed based on the multicast flow data bytes, number of hops between source and destination IEDs mentioned in the SCD file and process/station bus bandwidth.

The rest of the paper is organized as follows: section II describes GOOSE/SV transmission mechanisms and latency model. Section III illustrates the method for traffic segmentation followed by method for VLAN and multicast filter generation and Section IV describes the SCD file structure followed by the models for GOOSE/SV traffic estimation. Section V summarizes the results and provides the directions for future scope.

II. Transmission Mechanisms and Latency Model

A. GOOSE Transmission mechanism

GOOSE is a control model mechanism in which any format of data (status, value) is grouped into a data set and transmitted within a time period. GOOSE messages are exchanged at datalink layer, taking advantage of multicast functionality provided by Ethernet. The GOOSE communication consists of a fast event driven transmission and of a slow cyclic transmission. Upon occurrence of a preconfigured event, an IED sends GOOSE message containing values for the variables that needs to be communicated. Since these are multicast messages, there is no acknowledgement mechanism. Each GOOSE message has an attribute called Time allowed To Live (TTL) that informs the receiver about the maximum time that it must wait before the arrival of the next message. If a message does not arrive before the expiration of TTL, the receiver must assume that the connection was lost.

As shown in Fig. 1, to overcome transient errors, same GOOSE message is transmitted multiple times in a row, at interval T_1, then T_2 and T_3. T_0 is the maximum retransmission delay in steady state. T_{01} is the retransmission delay in steady state reduced by an event such as circuit breaker state change. T1 is the shortest retransmission delay upon an occurrence of an event while T_2 and T_3 are increasing retransmission delays as per the application. GOOSE messages are identified by their source MAC address and an identifier in the message. GOOSE transmission is based on publisher/subscriber principle. There is no queueing mechanism. The new value received replaces the former value. The state number within GOOSE message identifies whether the message is a new one or a retransmitted one.

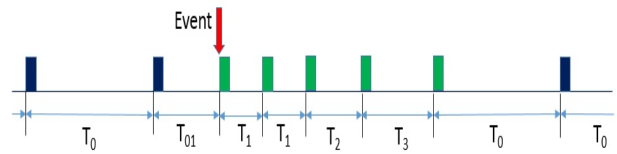

Fig. 1: GOOSE transmission mechanism

GOOSE traffic impacts more the station bus. GOOSE transmits messages cyclically and retransmits spontaneous messages, usually two times to overcome possible frame losses. This results in increase in traffic which becomes more than what is actually required. Since links have a very low loss rate, the recovery mechanism of GOOSE actually increases the probability of losing frames at switches due to congestion. A short GOOSE message handling just one digital status information in the dataset has an approximate size of 124 bytes. The actual size depends on various configured parameters in GOOSE control block such as GoID, name of dataset and reference object of GOOSE control block. Typical size of GOOSE message is between 92 bytes to 250 bytes. One GOOSE application in an IED generates about 1 Kbit/s in steady state and 1 Mbit/s during bursts.

B. SV Transmission Mechanism

The Sampled Values protocol is mainly used for transmitting analog measured samples such as voltage and current samples from sensors to IEDs. SV protocol uses OSI model Layer 2 for communication identified by MAC address and the identifier in the message body. There is no retransmission mechanism for SV messages. A lost sample is overwritten by next successful one and SV messages are transmitted cyclically with a timestamp. To avoid spurious jamming, all SV sources on the same bus should operate at the same period. They should preferably implement time division multiplex scheme. SV periodically send messages at a fixed rate, whose value depends on the frequency of the power system (4800 and 4000 message per second, for 60 Hz and 50 Hz power systems, respectively) [7]. SV frame size is around 150 bytes.

The process bus interconnects I/O devices like sensors and merging units at the field level. Typical traffic on process bus include GOOSE, SV, MMS and Precision Time Protocol (PTP). While GOOSE put similar requirements on process bus network as that on the station bus, SV is more hard real-time quality of service demanding, but SV traffic is easily predictable. For the process bus, some form of source throughput limitation must be applied to the real time traffic since because of its high priority, it could monopolize the network. This requirement should be met by the IEDs. In applications where station bus carries SV traffic, it must provide same quality of service as process bus.

C. Latency model

SAS performance depends significantly on communication network performance. The various communication elements such as bandwidth, message size, traffic on network etc. define the performance of communication network. IEC 61850 Part-5 characterizes the communication network performance by a term called transfer time (latency) which is the maximum time allowed for end to end message exchange between two devices. The transfer time includes processing as well as communication time. Fig. 2 specifies the transfer time t defined as complete transmission time of a message including the handlings at sender and receiver. In physical device PD1, a function f_1 sends data to another function f_2, located in physical device PD2. The transfer time will however consist of the individual times of the communication processors and the network transfer time, including wait times and time used by routers and other devices that are part of the complete network. In our proposed model we have considered t_a and t_c as 100 micro seconds based on the lab tests performed on the IEDs and t_b estimation is discussed in the section III C. IEC 61850 Part-5 further specifies the allowable message transmission latency requirements that needs to be used while designing and building substation functions and infrastructure. These latency specifications can be used to study the SAS network performance by comparing the estimated latency from SCD file.

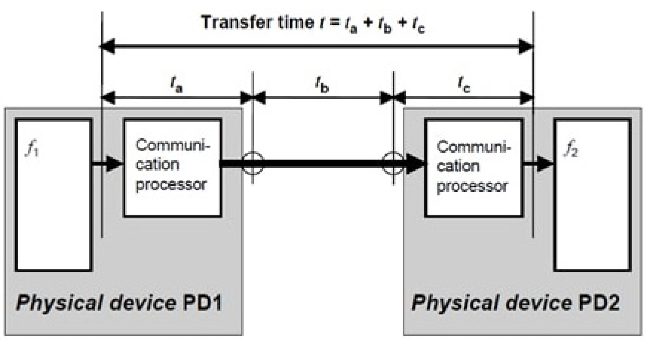

Fig. 2: Transfer time model for IEC 61850 data flows

III. OPTIMIZATION OF GOOSE/SV TRAFFIC SEGMENTATION

Segmenting the traffic based on the multicast data flowsthat are derived from SCD file aims at reducing the packet burst at the IEDs. After segmentation VLAN and multicast filtering is required limit the unnecessary traffic reaching the IEDs. Goal of optimization is to minimize the number of VLANs and Multicast filters that are configured in the SAS network switches. This is because the switches will have to process only a minimal set of VLANs and Multicast filters. Moreover, the effort needed to properly configure and test the network configuration during commissioning will also be reduced. A method for assigning optimal number of VLANs and multicast filters to the multicast flows in a substation automation (SA) network is described in this section. This methods adopts a new way of segmenting multicast traffic based on both VLAN and multicast address in SAS network. After applying the method, VLAN and multicast address filters are generated for each IED in the SCD file and this information can be further used for configuring the switch ports.

A. VLAN and Multicast Filters

VLAN is adopted to separate the traffic that share the medium. VLAN reduces the multicast traffic on edge links so that subscribing IEDs are not flooded with multicast messages. To support VLANs, the IEEE 802.3 frames carry a header, called the VLAN tag according to IEEE 802.1Q [8], which has two functions: prioritization of traffic and logical segregation of the traffic. Multicast address filters limit the distribution of multicast addressed frames (GOOSE and SV) to the subscriber ports that require the data, rather than simply transmitting the frame to all ports. This is achieved through static filtering, defined through the management interface of switch. However in the proposed method, multicast traffic segmentation is further optimized based on new grouping method and generate VLAN-IDs and Multicast Filter settings for IEDs based on the new groups.

B. Optimization Method

For an identified set of GOOSE/SV multicast flows from the SCD file, constraints for optimization are minimizing the number of VLANs and multicast filters in the SAS network. Set of publishers and subscribers for each GOOSE message flow is built from the SCD file data. Then, firstly, flows with publishers sending to same set of subscribers. Secondly, publishers sending messages to one another and to a common set of subscribers are grouped as MAC GROUPS as shown in the Fig. 3 and a unique GOOOSE/SV multicast address is assigned to the all flows in the MAC GROUP. The detailed steps involved in building MAC Groups are described in Algorithm 1.

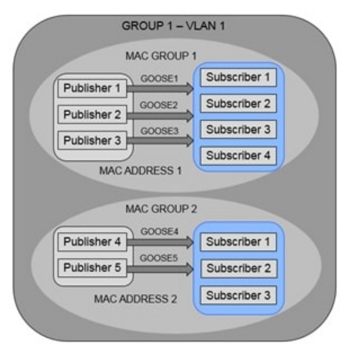

Fig. 3: Grouping for traffic segmentation

In this proposed method, traffic segmentation is optimized by using both VLAN and multicast address filtering. From Fig. 3 it is very clear that MAC GROUP 2 subscriber list

Algorithm 1: SCD file based multicast flow grouping

Input: X (Set of all GOOSE and SV flows);
$G \leftarrow \{\}$ (Initialize set of all flow groups);
$S \leftarrow \{SortedX\}$ (Sort the set X in descending order with respect to number of subscribers);
while *(Number of flows in $S \neq 0$)* **do**
  $T \leftarrow \{S[0]\}$ (Initialize current flow group);
  $F \leftarrow \{\}$ (Initialize set of remaining flows);
  $D_1 \leftarrow \{Dest(S[0])\}$ (Get subscribers of flow S[0]);
  $M_1 \leftarrow \{M \cup (S[0])\}$ (Get multicast address of flow S[0]);
  for *(i = 1 TO |S|-1)* **do**
    $D_2 \leftarrow \{Dest(S[i])\}$ (Get subscribers of flow S[i]);
    if *(D_1 = D_2) || (D_1∪Src(S[0]) = D_2∪Src(S[i]))* **then**
      $S[i] \leftarrow \{UpdatewithM_1\}$ (Set multicast address of S[i] to M_1);
      $T \leftarrow \{T \cup S[i]\}$;
    else
      $F \leftarrow F \cup S[i]$ (Add S[i] to the set of remaining flows);
    end
  end
  $G \leftarrow G \cap T$ (Add T to set of all flow groups);
  $S \leftarrow F$ (Update S with set of remaining flows);
end

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is the subset of MAC GROUP 1 subscriber set. Under such scenarios, MAC GROUP 1 and 2 PUB and SUBs are assigned with same VLAN ID and the steps involved in doing so are described in Algorithm 2.

Once the multicast address and VIDs are assigned to all the flows in the SCD file, filter tables for each IED are derived. These derived filters need to be configured on the switch port to which the relevant IED is connected. For a simple case of Fig. 3 only the Subscriber 4 is assigned with multicast filter with VLAN1 and MAC ADDRESS 1. Since Subscriber 1-3 subscribe from all the publishers in VLAN 1, they do not need multicast filtering as they can be filtered with VLAN 1 filtering only. Steps involved in deriving VLAN and multicast filters for the network switch's edge port are described in Algorithm 3. These filters have to be configured on the switch port to which a subscribing IED is connected.

For a given SAS network, GOOSE/SV flows should be routed such that every flow reaches its intended subscribers only. GOOSE and SV filters that are obtained from above method have to be applied to the physical communication network which is defined in the SCD file. This requires the derivation of appropriate VLAN and multicast filter settings for all switches in the network. The switch filter settings can be automatically generated from the SCD file based on a depth-first search algorithm. The algorithm works on a topology

Algorithm 2: SCD file based VLAN flow grouping

Input: G (Set of all multicast flows groups);
$H \leftarrow \{\}$ (Initialize set of multicast flow groups);
while *(Number of groups in $G \neq 0$)* **do**
  $T \leftarrow \{G[0]\}$ (Initialize current multicast flow group);
  $F \leftarrow \{\}$ (Initialize set of remaining multicast flow groups);
  $C_1 \leftarrow \{(SubscriberCountG[0])\}$ (Get the number of subscribers in a flow of current group);
  $G[0] \leftarrow \{V_{NEW}\}$ (Assign new VLAN ID to the current group);
  for *(i = 1 TO |G|-1)* **do**
    $C_2 \leftarrow \{(SubscriberCountG[i])\}$ (Get the number of subscribers in a flow of ith group);
    if *($C_2 \geqslant C_1/2$)* **then**
      $G[i] \leftarrow V_{NEW}$ (Update VID of G[i] group flows with V_{NEW});
      $G[0] \leftarrow G[0] \cup G[i]$;
    end
  end
  $H \leftarrow H \cup G[0]$;
  $G \leftarrow G - G[0]$ (Remove VID assigned groups from G);
end

Algorithm 3: Multicast filters for the IEDs in SCD file

Input: H (Set of all optimized flow groups);
$ListIED_{SUB} \leftarrow \{\}$ (Initialize Subscribing IED list));
$T_1 \leftarrow \{\}$ (Initialize IED-VID table));
$T_2 \leftarrow \{\}$ (Initialize IED-VID-Multicast address table));
$G \leftarrow \{\}$ (Initialize a flow group);
for *(i = 1 TO |H|-1)* **do**
  $ListIED_{SUB} \leftarrow \{IED_{SUB}(H[i])\}$ (Update IED List with all subscribing IEDs of H[i]);
  $G \leftarrow H[i]$;
  for *(each IED_{SUB} in $ListIED_{SUB}$)* **do**
    if *($IED_{SUB} \notin$ G)* **then**
      (IED_{SUB} doesn't belong to all flows of H[i])
      for *(j = 1 TO |G|-1)* **do**
        $T_2 \leftarrow \{IED_{SUB}(VID[i], MCAddress[j])\}$ (Update T_2 with subscribing IEDs, their VID[i] and MCAddress[j]);
      end
    else
      $T_1 \leftarrow \{IED_{SUB}(VID[i])\}$ (Update T_1 with subscribing IEDs and their VID[i]);
    end
  end
end

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model derived from the communication section of the SCD and is described in [9]. However, usually trunk links in SAS network will have high bandwidth and configuring the VLAN and multicast filters only on the edge ports (derived from algorithm 3) of the switches will be sufficient to prevent the traffic flooding at the IED ports.

IV. MODEL FOR GOOSE/SV TRAFFIC ESTIMATION

In [10] GOOSE and SV frame size ranges are tabulated, and the paper analyzes the process bus performance for shared and redundant network. In [11] simulation models for GOOSE and SV messages are proposed and [12] offers the OMNeT++ based simulation of IEC6180 compliant substations. In this section, we propose model for traffic estimation deduced from SCD file information only. The model derives the frame size of GOOSE/SVframes, considers the protocol transmission mechanism and evaluates the bandwidth required and latency expected.

A. *Model deduction from SCD file*

An SCD file contains substation, communication, IED and data type template section. The substation part of SCD file deals with different entities of substation which includes protection and control devices, interconnections and other functionalities. In SCD file logical nodes represent functionality related to an object in substation and logical communication flow defines publishing IED and set of subscribing IEDs for a given GOOSE/SV message. In this section, methods to estimate the GOOSE/SV traffic based on the logical communication flow mentioned in the SCD file is described. Datasets transferred between different IEDs are specified in the communication section of the SCD file. Each dataset will be containing different data objects. The data objects in turn are composed of data attributes. The size of each dataset is calculated by summing up the size of all attributes contained in it. The size of data attributes are estimated based on part 7-3 of IEC 61850.

B. *GOOSE Traffic Estimation Model*

The structure of GOOSE message is described IEC 61850-8-1. For time critical events, GOOSE messages are exchanged between IEDs over Ethernet network. GOOSE service uses application layer, data link layer and physical layer of the OSI model. Only one Dataset may be assigned to each transmitting message. To avoid sending multiple messages from each relay to cause network latency, all desired data to be sent should be incorporated in the same Dataset [13].

A GOOSE message frame consists of header MAC, Priority tag information, Ethernet PDU and GOOSE APDU [14]. Header MAC includes the fields Destination ID and Source ID. Both are of the form 01-0C-CD-XX-XX-XX. Priority tagged information consists of the fields TPID (Tag Protocol Identifier), TCI (Tag Control Information) fields which are User priority field and VID. If VLAN is not used then VID is set to zero. Ethernet type, APPID and Length are part of Ethernet PDU. The GOOSE APDU consists of stNum (state Number), sqNum (sequence Number), TAL (Time Allowed to Live), ndsCom (needs Commissioning), confRev (configuration Revision), numDatsetEntries (number of dataset entries), gocbRef (GOOSEcontrolblockReference), goID (GOOSE ID), Datset, Timestamp and All data. All DATA fields which belong to GOOSE APDU are preceeded by TAG and LENGTH fields. This is as per Basic Encoding Rules in Abstract Syntax Notation 1 (ASN.1). GOOSE message structure is depicted in the Fig.4. In GOOSE frame gocbRef, Dataset Name, goID and

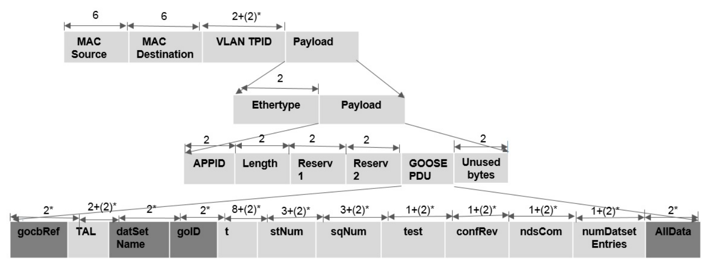

Fig. 4: GOOSE Message Structure

All data have variable size. All other fields have fixed bytes. In Fig.4 dark shaded fields are of variable size. Each variable size field will be having tag and length of 2 byte size. Size of variable size elements in GOOSE frame is calculated using the data attributes contained inside the dataset information from SCD file. Total GOOSE message size in bytes is estimated as sum of fixed byte size (72 bytes) and variable byte size.

SAS network has publishing and subscribing IEDs and GOOSE messages travelling in the network. Events occur in SAS whenever there is the binary or analog input coming from the field devices has changed (external events), and also as a result of internal computation in an IED (internal events). When events occur in SAS, related GOOSE messages will burst into the network and IEDs in the network may be overloaded with traffic. Bandwidth is estimated using the calculated size of message in bits (G_{bits}) and transmission time information obtained from SCD file. SCD file we considered contains min time (T_1) and max time (T_0) values using which steady state bandwidth is calculated as message bits transmitted per max time, whereas, burst mode bandwidth is calculated as the message bits transmitted per min time. After calculating the GOOSE message size (G_{bits}) from SCD file, bandwidth required for that message during burst mode and steady state are calculated as shown in equation (1) and (2) respectively.

$$BW_{bm} = G_{bits}/T_1 \tag{1}$$

$$BW_{ss} = G_{bits}/T_0 \tag{2}$$

If subscribing IED ($SIED_i$) is receiving k GOOSE messages, resultant bandwidth is calculated as sum of bandwidth required for each of GOOSE messages given by the equations as below. Equation (3) describes the worst case bandwidth requirement while (4) describes the best case.

$$BW_{bm} = \sum_{j=1}^{k} G_{jbits}/T_{j1} \tag{3}$$

$$BW_{ss} = \sum_{j=1}^{k} G_{jbits}/T_{j0} \quad (4)$$

For an (SIED$_i$), best case to worst case bandwidth utilization estimation can be expressed as:

$$BW_{ue} = \sum_{x=1}^{e} G_{xbits}/T_{x1} + \sum_{x=e+1}^{n} G_{xbits}/T_{x0} \quad (5)$$

where, e (0 to n) is the number of events occurring in segmented or unsegmented network which cause GOOSE messages G$_1$....G$_n$ that are subscribed by SIED$_i$. Suppose set of events e$_1$, e$_2$...e$_n$ occur at time t, then related GOOSE flows G$_1$,G$_2$...G$_n$ first change their data rate to T$_1$, which is the highest data rate of GOOSE flows. Subsequently, the data rate declines exponentially (as per the application) until it returns to T$_0$. This change of data rate causes a traffic burst in a period of time T$_0$, so is called the bursting period. Since T$_1$ is usually very short and the data rate does not exceed T$_1$. For a given subscribing SIED$_i$, BW$_e$ is used to provide the behavior of required bandwidth for that IED between no event system and all events occurring in the system.

C. SV Traffic Estimation Model

SV frame contains field APDU (Application Protocol Data Unit) within which the SV data is encapsulated. APDU is in Tag, Length, and Value format. Every SV packet is created by SV publisher application and upon creation consists of a series of SV ASDUs (Application Service Data Units) encapsulated inside SV APDU [15]. The byte structure of SV ASDU and SV APDU is based on Basic Encoding Rules specified in ASN.1. The APPID field stands for application identifier and is used to select those Ethernet frames which contain SV APDU, and to distinguish between GOOSE and SV protocol. The length field indicates length of SV packet including SV specific header. If length of APDU is *m* bytes, length field shall be set to *m*+8 since the length of SV specific header is 8 bytes. Reserved1 and Reserved2 bytes are for future applications and for security purposes.

SV message size can be divided into fixed size and variable size. Fixed and variable size fields of SV with their size in bytes are shown in Fig. 5 savPDU contents will be having field label and length values. These two bytes are also considered for size calculation. The size of fixed bytes of SV messages is calculated to be 49 bytes. With the pre-calculated fixed bytes and variable bytes obtained from SCD file, total SV message frame size is deduced. This size is used for bandwidth estimation. In Fig. 5 dark shaded regions are fields of SV message having variable size and * indicates size of tag and length for that field. SV message shown in Fig. 5 is having only one ASDU. Many ASDUs can be concatenated within a SAV PDU and can be sent. Unlike GOOSE messages, SV messages are transmitted at fixed rate (smpRate) which is specified in the SCD file. In SCD file, sampling modes can be mentioned in three different formats: samples per period, samples per second, seconds per sample. Default format is samples per period. Bandwidth calculation for each format

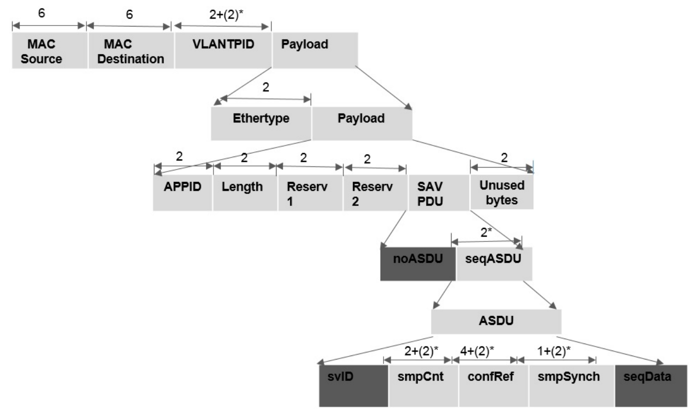

Fig. 5: SV message structure

TABLE I: BANDWIDTH CALCULATION FOR DIFFERENT SAMPLE MODES

Sample mode	Bandwidth calculation formulae
SmpPerPeriod	Message size x SmpPerPeriod x grid frequency
SmpPerSecond	Message size x SmpPerSecond
SecPerSample	Message size/SecPerSample

is given in TABLE I. SV bandwidth estimation is similar to GOOSE bandwidth estimation except that SV bandwidth calculation uses Sample mode instead of min time and max time of GOOSE. As an example, an SV frame with a sampling rate of 80 samples per cycle transmitted at 4,0 kHz (for a 50 Hz grid) or at 4,8 kHz (for a 60 Hz grid) have an approximate size of 140 bytes, consuming a bandwidth of approximately 5 Mbit/s (50 Hz) or 6 Mbit/s (60 Hz) per source IED. The maximum latency when there is no packet loss is expected to be 250 μs [16].

D. Flow Latency Estimation

Latency of communication is the delay between the instant when data are ready for transmission and the moment they have been completely received at their destination(s). Communication latency is composed of transmission delay, propagation delay, processing delay and queuing delay. TABLE II shows the allowable ranges of transfer time classes for monitoring, protection and control applications within substation. The trip and blocking from protection function category, are the most time critical messages that need up to 3ms transfer time for adequate performance. Events and alarms from monitoring function category, are not stringent on latency specification as they require up to 500 ms transfer time for specified performance. The network also contain less time critical messages like file transfer functions and report request functions, time synchronization messages which are not in the scope of this research.

The correct design of a network to be used for IEC 61850 communication requires knowledge of the application requirement and the knowledge of latencies caused by various network elements. For a given GOOSE/SV flow, minimum, average and maximum latency is calculated as a sum of

TABLE II: GOOSE/SV TRANSFER TIME CATEGORIES

Transfer time class	Max transfer time (ms)	Application examples
Very fast messages	3	Protection commands: Trips, reclose, blockings etc.
Fast messages	20	Start, stop, states etc.
Medium speed messages	100	Measuring value, status changes
Low speed messages	500	Alarms, non- electrical measurements
Raw data messages	0.2	Current and voltage measurements (SV)

physical path latency, and switch latency based on hop counts. A physical path delay is caused by the finite speed of the electromagnetic waves through the medium: copper cables, optical fibers or wireless links. Physical path delay in the latency estimation is assumed to be 0.50 micro seconds. And communication module processing time at IEDs: t_a and $t_c$is assumed as 100 micro seconds.

Whenever a frame arrives at a switch ingress port, most switches wait for the complete frame to be received to check its integrity (using its CRC field) before it is forwarded. This technology is called store-and-forward. Store-and-forward switch latency includes elapsed time of ingress and egress ports (depending on link speed), internal processing delay, in particular protocol processing, and queueing delays. In the prototype implementation queueing delays are ignored as they depend on load and QoS settings on the network switches. Formulae used for flow latency calculation based on hop counts are mentioned in (6) to (8)

$$Latency_{min} = (n \times (\frac{b}{B})) + 8\mu s \tag{6}$$

$$Latency_{max} = (n \times (\frac{b}{B})) + 132\mu s \tag{7}$$

$$Latency_{avg} = (n \times ((\frac{b}{B}) + 132\mu s)) + (n-1) \times (70\mu s) \tag{8}$$

where number of hops = n, GOOSE/SV frame bits = b, Link Bandwidth in 100 Mbps = B. In a non-congested network, for a GOOSE message with 300 bytes, the minimum switch hop latency at 100Mbit/s is estimated to 32μs. The switches usually operate in a store-and-forward mode, which means the whole frame is received before it is forwarded. A typical GOOSE message has 2400 bits, and causes at 100Mbit/s a delay of 24μs. With a minimum switch latency of 8μs + frame delay, the latency is 8μs+ 24μs = 32μs. For the worst case latency a delay caused by one 530 byte frame queuing wait for each hop is considered, however the probability that this happens is low.

V. Results

Proposed methods and models are implemented in .NET 4.5 environment and the developed tool takes SCD file as an input. SCD file of a real substation is considered for the traffic segmentation, analysis, estimation and evaluation. SCD file contains 42 IEDs, 220 GOOSE flows, and 23 datasets. Proposed segmentation methods are applied this SCD file and 39 VLAN groups have been formed. Implementation of proposed method automatically generates the VLAN and multicast filters after analyzing the SCD file and such filters are mentioned in TABLE III and IV for selected IEDs. From

TABLE III: IEDS WITH VLAN FILTERING

IED Name	VLAN Groups
AA1B1Q05A1	2, **4**, **7**, 11, 25, 33
AA1B1Q15A1	2, **3**, 4, **5**, 6, 12, 19, 20, 21
AA1B1Q10FP1	**27**, 36
AA1C1Q06A1	2, **7**, **8**, **9**, **10**, 11, **13**, 22, 31
AA1C1Q10A1	2, 24, 30, 39
AA1C1Q09FP1	28,38

TABLE IV: IEDS WITH VLAN AND MULTICAST ADDRESS FILTERS

IED Name	VLAN Groups	Multicast address filters
AA1B1Q05A1	4 7	010CCD010002 010CCD010005/09/1D
AA1B1Q15A1	3 5	010CCD010001 010CCD010003
AA1B1Q05A1	27	010CCD010022
AA1C1Q06A1	7 8 9 10 13	010CCD010005/2D 010CCD010006 010CCD010016/26 010CCD010008 010CCD01000C

the TABLE III and IV we can infer that for some IEDs such as AA1C1Q10A1 and AA1C1Q09FP1 just need VLAN filter at the connected switch edge port. Such IEDs in a given VLAN group receive all the GOOSE messages that are intended for them. However IEDs such as AA1B1Q05A1 need both VLAN and multicast filter configured at switch edge port. Since such IEDs are receiving unwanted GOOSE messages in a VLAN group, they are further filtered by multicast address filtering.

Using proposed traffic estimation model, bandwidth requirement for an IED in flat as well as segmented network is shown in Table V. It can be clearly seen that, number of messages received in segmented network are considerably reduces in segmented network and hence IEDs are less loaded with the traffic. There is a drastic change in the link utilization, and thus edge links are relieved from traffic burden. Considering the 100 Mbps station bus estimated traffic bandwidth gives clear indication of availability of sufficient bandwidth for the developed application and possibility of scaling up the network based on further requirement. The link utilization varies greatly during the occurrence of event and TABLE V provides worst case bandwidth requirement (during bursts) which is critical from the network planning perspective.

Bandwidth doesn't directly affect the flow latency. However the number of hops between the publisher and the subscriber can affect the transfer time dramatically. Fig. 6 depicts the comparison of transfer time of a GOOSE flow mentioned in the SCD file for 100 Mbps and 1 Gbps link. For each case, minimum, average, and maximum switch latencies are calculated as per the equations (6), (7), and (8). The interesting pattern that is observable from the figure is that the average

TABLE V: TRAFFIC ESTIMATION OF SEGMENTED AND FLAT NETWORK

IED Name	Flat network			Segmented network		
	G_n	BW_{bm} (Mbps)	BW_{ss} (kbps)	G_n	BW_{bm} (Mbps)	BW_{ss} (kbps)
AA1B1Q05A1	213	67.677	33.322	14	12.457	4.982
AA1B1Q15A1	206	65.497	32.351	15	14.003	5.601
AA1B1Q10FP1	220	70.015	34.158	1	0.703	0.281
AA1C1Q06A1	205	65.242	32.249	15	14.302	5.721
AA1C1Q10A1	214	68.047	33.371	7	9.439	3.775
AA1C1Q09FP1	219	69.654	34.044	1	0.139	0.699

and maximum latencies diverge considerably with the increase in the number of hops. More number of hops may lead to high probability of considered flow going through queueing delays at switch ports thereby increasing the transfer time. With this consideration, it is very important to plan the network topology in such a way that number of hops between publishing and subscribing IEDs are minimized.

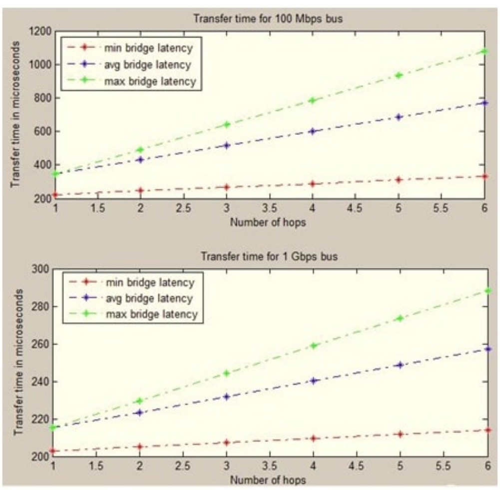

Fig. 6: Transfer time estimation

VI. Conclusion

In this paper, we proposed the method for optimized network segmentation for Layer 2 SAS network and generating VLAN and multicast filters for the IEDs from SCD file flows. The latter part we have focused on traffic estimation theory and methods to estimate the bandwidth required for IEDs in both flat and segmented network. Nevertheless, flow latency estimation model is developed which brings the comparison between the estimated flow latency based on SCD data flows and the standard latency requirements. With the achieved results it can be concluded that systematic traffic segmentation can drastically reduce the traffic at the IEDs in SAS network. This will also reduce the network traffic congestion as set of traffic flows are restricted only to the required paths in the SAS network.

Moreover, bandwidth and latency estimation model would provide a greater value during the network planning and scaling. For the planning and building of SAS network, it is beneficial for communication engineers to evaluate the performance of developed application (SCD) based on the traffic and data flow models which are proposed in this paper. A desirable network can be achieved with these evaluations and this enables bandwidth management and load balancing in underlying SAS network. With respect to future work, one of the research directions would be explore accurate traffic model to precisely schedule and allocate the SAS network link bandwidth based on the network topology, and then control the traffic direction and improve routing strategies which will finally improve the SAS network performance.

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