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Context Aware Traffic Scheduling Algorithm for Power Distribution Smart Grid Network

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ABSTRACT The emergence of smart grid poses technical challenges to the power distribution network because of the increasing data traffic resulting from diverse data applications. Traffic scheduling algorithms manage these heterogeneous applications by applying different priorities to each traffic type based on its quality of service (QoS). However, QoS alone cannot accurately capture complex situations wherein packets with low priority occasionally need to be served first based on their context, resulting in a suboptimal solution. This paper proposes a context aware traffic scheduling (CATSchA) algorithm to schedule the traffic such that it could adapt to varying power network conditions. The power distribution network traffic is characterized based on heterogeneous traffic demands, and then mapped into weighted quality classes. The CATSchA algorithm is implemented in a packet switched network using NS-3 simulator, and the traffic demand is fulfilled based on the algorithm's context awareness. Compared with traditional traffic scheduling algorithms, the proposed algorithm lowers the delay while maintaining the throughput and link efficiency.

INDEX TERMS Context aware, traffic scheduling, quality of service, smart grid.

I. INTRODUCTION

Apower grid comprises three main divisions, namely generation, transmission, and distribution, which distribute power to consumer. The distribution division distributes stepped down generated power via multiple substations to consumers. Each division plays vital roles in delivering electrical power to users. Present conventional power grid is being transformed into a smart grid. The conventional power grid is supported by one-way communication network [1], whereas the smart grid is supported by two-way communication network for several types of data that require robust and scalable infrastructure [2].

Generally, the power distribution network comprises streams of data to be transmitted from multiple sites to a control center. Use of smart grids poses technical challenges on the network because of increasing data traffic. By adopting advanced metering infrastructure (AMI), which is one of the major enabling technologies for smart grid, the number of smart meter (SM) readings will increase from 24 million a year to 220 million per day [3].

Apart from the SM, several other applications exist in the power distribution network. These applications have various quality of service (QoS) requirements that need proper handling. In order to manage these, traffic scheduling algorithms have been proposed in power grid such as in [4] and [5]; these algorithms are implemented in circuit switching technology. However, with the evolution of new Ethernet-based applications and the declining rate of circuit-switched products and expertise, packet switched technology for power system network have emerged. Hence, a traffic scheduling algorithm must be used in a packet switched network.

Traffic scheduling algorithms have been proposed for the power grid in a packet switched network [6]–[14], wherein the priority assignment of traffic types is defined based on their QoS. When fully relying on the QoS, the algorithm does not accurately capture complex situations. For example, packets with considerably low priority need to be served first based on their context. Thus, a suboptimal solution is obtained if the assignments depend only on the QoS.

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TABLE 1. Nomenclature.

Acronym	Definition
AGTS	Adaptive Guaranteed Time Slot
AMI	Advanced Metering Infrastructure
AQoS	Adaptive Quality of Service
CATSchA	Context Aware Traffic Scheduling
CCTV	Closed Circuit Television
DCN	Data Center Network
DSCP	DiffServ Code Point
EXP	Experimental
IED	Intelligent Electronic Device
IP	Internet Protocol
MOQoS	Matrix of QoS
MPLS	Multiprotocol Label Switching
MPTCP	Multi Path Transmission Control Protocol
OMC-RPL	Optimized Multi-Class of Routing Protocol for Low Power and Lossy
QoS	Quality of Service
RFPD	Radio Frequency Partial Discharge
RIO	Random Early Detection with In/Out Bit
SCADA	Supervisory Control and Data Acquisition
SDN	Software Defined Network
SM	Smart Meter
SR	Segment Routing

Herein, we address the issue of adaptive traffic scheduling for different contexts or situations. The power distribution applications are characterized into different classes according to their traffic demand; these classes are then prioritized based on their context information. Main contributions of this paper are as follows:

- Characterization and prioritization of heterogeneous power distribution network traffic in a distribution network into multiple traffic classes based on its context and QoS.
- Development of Context Aware Traffic Scheduling (CATSchA) algorithm for smart grid in a packet switched technology environment.
- Evaluation of the CATSchA algorithm via simulation using NS-3, which demonstrates improved delay while maintaining high throughput and efficient bandwidth utilization compared with algorithms without context aware.
- Evaluation of scalability and suitability of CATSchA algorithm, which will be implemented in a more complex topology.

The remainder of this paper is organized as follows: Section 2 reviews related work; Section 3 presents the heterogeneous distribution traffic characterization and prioritization. Section 4 introduces the proposed CATSchA algorithm with theoretical explanations, and the simulation setup and evaluation of the varying traffic loads with regard to throughput, delay, and efficiency are described in Section 5. Section 6 concludes the paper. Table 1 lists the acronyms and notations used in the paper.

II. RELATED WORKS

Over the years, several traffic scheduling algorithms have been developed in packet switching technology for power distribution networks [6]–[14]. Among them are Multi Path Transmission Control Protocol (MPTCP) with segment routing (SR) in multi-rooted data center network (DCN) topologies proposed by Pang *et al.* [6] and Radio Frequency Partial Discharge for condition monitoring and integrating sensor signals into a smart grid monitoring system proposed by Baki *et al.* [7]. Pang *et al.* [6] was among the first researchers who combined MPTCP and SR. A four-layer DCN architecture comprising physical topology, SR over the topology, multiple path selection provided via MPTCP, and traffic scheduling on the selected paths is used to obtain better throughput and utilization. The traffic scheduling in [6] functions in such a way that more flows will be granted to the route that efficiently performs. Multiprotocol Label Switching (MPLS)-based QoS mechanism is also briefly discussed [7], revealing that the MPLS technology is suitable for dynamic monitoring of smart grid devices. The focus of these two papers are on dynamically allocating the bandwidth, rather than prioritizing the traffic based on the QoS.

Alishahi *et al.* studied traffic prioritization without context aware characteristics [8] by proposing an Optimized Multi-Class of Routing Protocol for Low Power and Lossy network (OMC-RPL) as the virtual version of the RPL protocol. In OMC-RPL, four traffic classes are categorized based on weighting parameters, including required delay and packet loss. Alhowaidi *et al.* [9] proposed Greedy-Heuristic algorithm to resolve the problem of resource scheduling and bandwidth assignment to satisfy dynamic demands in a cloud network. Al-Anbagi *et al.* introduced an adaptive QoS (AQoS) scheme and Adaptive Guaranteed Time Slot (AGTS) allocation scheme for delay critical smart grid applications in the distribution division [10]. AQoS scheme was implemented in a cluster-tree topology to adaptively modify the guaranteed time slot based on a request made from the end devices, whereas the AGTS scheme was applied on a mesh topology to dynamically tune the time slots based on various traffic and network conditions. These schemes can be further improved by considering context aware prioritization to ensure that the traffic can be adaptively scheduled based on their current demands.

Kamoun *et al.* [11] proposed an Internet Protocol (IP) hard pipe approach in MPLS network. The hard pipe stratum can guarantee a time slot for each critical traffic flow such that there is no contention between different flows. All the traffic is encapsulated with MPLS label, and a dedicated tunnel is exclusively reserved with respect to specific traffic that possesses the same labeling. Therefore, routers can differentiate hard pipe traffic from soft pipe traffic. Hard pipe services are scheduled for high-priority traffic, whereas soft pipe services are scheduled for normal MPLS traffic with low priority. For this approach, the transmission between high- and low-priority traffic is fixed with its dedicated tunnel, regardless of its context.

QoS guarantee in smart grid infrastructure has been implemented using Random Early Detection with In/Out Bit (RIO) algorithm, which is based on queuing discipline communication via traffic classification [12]. Applications are categorized into four traffic classes based on the DiffServ principles: Class 1 for low delay and low packet loss traffic; Class 2 for high bandwidth, low delay, and low packet loss traffic; Class 3 for moderate bandwidth traffic; and Class 4 for delay-tolerant traffic. These traffic classes are prioritized based on service delivery time and required bandwidth; then, DiffServ Code Point (DSCP) is assigned to each packet before transmission. This algorithm entirely treats the traffic based on its QoS without adaptively changing the priority based on its context. Herein, we aim to change the traffic priority based on its context, which has a huge advantage.

The drawback of priority assignment based on QoS becomes evident in situations wherein packets with lower priority need to be served or transmitted first based on their context. For instance, surveillance cameras that have lower priority might need to be served first in cases wherein possible intrusion is detected. Traffic priority must be redefined because the context of data may periodically change [13]. Traffic scheduling algorithm in smart grid network needs to be aware of traffic with unusual data based on its situation to ensure reliability and timeliness of critical data.

To address this issue, Rezaee *et al.* [14] presented the Wide Area Measurement System communication infrastructure using software-defined networking (SDN) technology to measure, collect, and analyze data in a power system. Two traffic classes were considered and context aware Active Queue Management was implemented to improve delay performance by dropping less important packets that contain older data. Therefore, the available bandwidths were assigned to high-priority packets that contained newer data. Herein, the performance of delay, jitter, bandwidth, and fairness are improved using the proposed algorithm. The context aware part of the proposed algorithm is defined to drop packets containing older data rather than taking them into account to be transmitted. This is a disadvantage because low-priority data will be prone to delay. For longer queues, the packets may be dropped altogether, in turn, affecting the reliability of the system.

To systematically handle all the traffic based on previous studies, we propose CATSchA algorithm for traffic prioritization, where ranking can be rearranged based on their criticality and sensitivity. Using the context aware in scheduling various traffic classes in the smart grid, each traffic propriety can be dynamically changed based on its context. Rather than dropping lower priority packets, they will be queued and served only after all the high-priority packets are served to maintain the reliability of the system.

III. TRAFFIC CHARACTERIZATION

Traffic in smart grid is categorized based on its specific requirements in a power distribution network, which produces a set of predefined priorities. To support various service quality requirements of heterogeneous traffic from smart grid applications along with its varying context, the traffic requirements are modeled based on distinct priority classes.

TABLE 2. Traffic classes for smart grid applications with service parameters.

Classes	Data Size	Data Rate	Delay
Limited size/Critical rate/Real time ($S_1R_1D_1$)	Small	Low	Small
Limited size/Critical rate/Non-real time ($S_1R_1D_0$)	Small	Low	High
Limited size/Noncritical rate/Real time ($S_1R_0D_1$)	Small	High	Small
Limited size/Noncritical rate/Non-real time ($S_1R_0D_0$)	Small	High	High
Unlimited size/Critical rate/Real time ($S_0R_1D_1$)	Large	Low	Small
Unlimited size/Critical rate/Non-real time ($S_0R_1D_0$)	Large	Low	High
Unlimited size/Noncritical rate/Real time ($S_0R_0D_1$)	Large	High	Small
Unlimited size/Noncritical rate/Non-real time ($S_0R_0D_0$)	Large	High	High

Typically, smart grid distribution network contains distinctive traffic from teleprotection, Supervisory Control and Data Acquisition (SCADA), online monitoring system, SM, Internet, closed-circuit television (CCTV), WiFi, smart building automation system, indicator control, and fault recorders. The traffic is mapped to its respective traffic class, as shown in Tables 2 and 3, by considering its QoS specifications. Four different traffic types from SCADA, SM, CCTV, and Internet are selected for testing in the CATSchA algorithm.

Let C be the set of priority classes; each class is attributed to quality parameters, namely data size in binary, S_x^c, data rate in binary, R_y^c, and delay in binary, D_z^c, of x, y, and z service parameters passing through any router. Herein, data size is defined in terms of various packet sizes for different traffic types transmitted in a power distribution network represented in *Bytes*. The data rate represented in *bps* is defined by the speed of packets transmitted from the source to the destination for each traffic type. Delay is defined in terms of end-to-end packet delay of previous packet transmission over selected route given in seconds (s). Finally, the service parameters x, y, and z are defined in terms of 0s and 1s for each traffic depending on their inputs. The number of flows belonging to each class is described in the corresponding flow set, $F_c(t)$. Thus, the traffic flow, $F_c(S_x^c, R_y^c, D_z^c)$ belonging to a particular traffic class C will use the respective time slots. These three parameters are chosen to monitor the QoS of the selected four traffic types.

S_1 denotes small data size (SCADA and SM), and S_0 denotes large data size (CCTV and Internet). R_1 represents low data rate required for transmitting SCADA and SM traffic, whereas R_0 indicates high data rate for packet transmission of CCTV and Internet. D_1 represents small end-to-end delay (SCADA and CCTV), and D_0 denotes high end-to-end delay (SM and Internet).

SCADA is characterized by traffic with small data size because its packets carry only a small size of information collected from the field. The packets are continuously transmitted to a control center comprising real-time data received

TABLE 3. Smart grid application mapping to traffic classes and their context identities.

Smart Grid Applications	Traffic Classes	Context Identities
Teleprotection	$S_1R_1D_1$	High speed protection information
SCADA	$S_1R_1D_1$	Data poll response
SM	$S_1R_1D_0$	AMI-periodic measurements
Smart building automation system	$S_1R_0D_1$	Energy conservation, comforting lifestyle
Fault isolation and service restoration	$S_1R_0D_0$	Reporting distribution applications function
Online monitoring system	$S_0R_1D_1$	Monitoring and alarm system
Fault recorders	$S_0R_1D_0$	Power quality monitor/recorder
CCTV	$S_0R_0D_1$	Theft, trespassing reporting, accident reporting
WiFi	$S_0R_0D_0$	Social network integration
Internet	$S_0R_0D_0$	Enterprise data

from Intelligent Electronic Device (IEDs) relays, and bay controllers connected to the power utility system. Therefore, a low data rate is required for transmitting the small data size for this traffic. SCADA is also characterized by small delay traffic because it cannot tolerate delays; it provides an active operator interface for supervisory control and remote configuration of IEDs and other devices. Large delay causes huge production losses from flashover due to late commands or switching actions performed on devices in a substation.

SM is characterized by traffic with small data size because its packets carry only meter readings of energy usage from customer premises and demand response, which are required for transmission, typically once a month for billing purposes. Thus, a low data rate is necessary for packet transmission of this traffic to the control center. SM is able to tolerate high delay traffic because it contains non-real time data; thus, it can handle large delays for successful transmission.

In contrast, CCTV is characterized by traffic with large data size because its packets carry video information from each substation across the country; thus, it requires high data rate for transmission to the control center. CCTV is characterized by small delay traffic because it cannot tolerate delay as video disruption may interfere with the monitoring of the substation. By default, CCTV is always on standby mode because it is only triggered when the traffic is on demand.

Internet is characterized by traffic with large data size because its packets carry data information to serve internal communication inside the control center and as external communication between other regional master stations. Hence, this traffic requires a high data rate for packet transmission to ensure successful communication. Internet is also categorized as high delay traffic because it can tolerate a high amount of delay in a power grid as opposed to its importance in carrier network.

Table 4 shows a predefined priority ranking for each traffic after the traffic has been characterized. SCADA is the

TABLE 4. Predefined traffic priority ε_c^i ranking.

Traffic	Characteristics	Symbols	Data Size (S_x)	Data Rate (R_y)	Delay (D_z)	Rank
SCADA	- small data size - low data rate - small delay	$S_1R_1D_1$	1	1	1	1
SM	- Small data size - Low data rate - High delay	$S_1R_1D_0$	1	1	0	2
CCTV	- Large data size - High data rate - Small delay	$S_0R_0D_1$	0	0	1	7
Internet	- Large data size - High data rate - High delay	$S_0R_0D_0$	0	0	0	8

TABLE 5. Threshold values of each traffic type.

Traffic	Data Size, $S^c_{threshold}$ (Bytes)	Data Rate, $R^c_{threshold}$ (bps)	Delay, $D^c_{threshold}$ (sec)
SCADA	41.67	20	4.5
SM	50	40	7.5
CCTV	203.80	150	2.5
Internet	446.43	250	8.5

highest-ranked, and it is fixed throughout the algorithm. Moreover, SCADA is responsible for delivering real-time information; therefore, it should have the best characteristics among all applications in a power distribution network. SM ranks second, followed by CCTV and Internet ranked last. The application-to-class mapping for traffic other than SCADA will vary at runtime based on the variable context information; this information includes data size, data rate, and delay. Hence, an application is mapped to a particular class based on its criticality as per context aware priority, ε_c^j.

The priority of class C in data delivery is defined in terms of its predefined priority ε_c^i, as well as in terms of its context aware priority, ε_c^j. The predefined priority factor, ε_c^i defines the initial priority of class C for allocating resources. While the parameter ε_c^j represents the context aware priority of class C, whose predefined priority is ε_c^i.

Each class is bounded by the minimum and maximum threshold values of data size (S^c_{min}, S^c_{max}), data rate (R^c_{min}, R^c_{max}), and delay (D^c_{min}, D^c_{max}). Ranges of data sizes for SCADA are obtained from the study reported by Kuzlu *et al.* [15], whereas the delay ranges are acquired from IEEE Standard Communication [16]. Both ranges of data sizes and delays of SM and CCTV are obtained from the study reported by Kuzlu *et al.* [15]. Standardized data sizes and delays for the Internet are obtained Uribe *et al.*'s study [17]. The threshold values are selected based on these ranges as shown in Table 5.

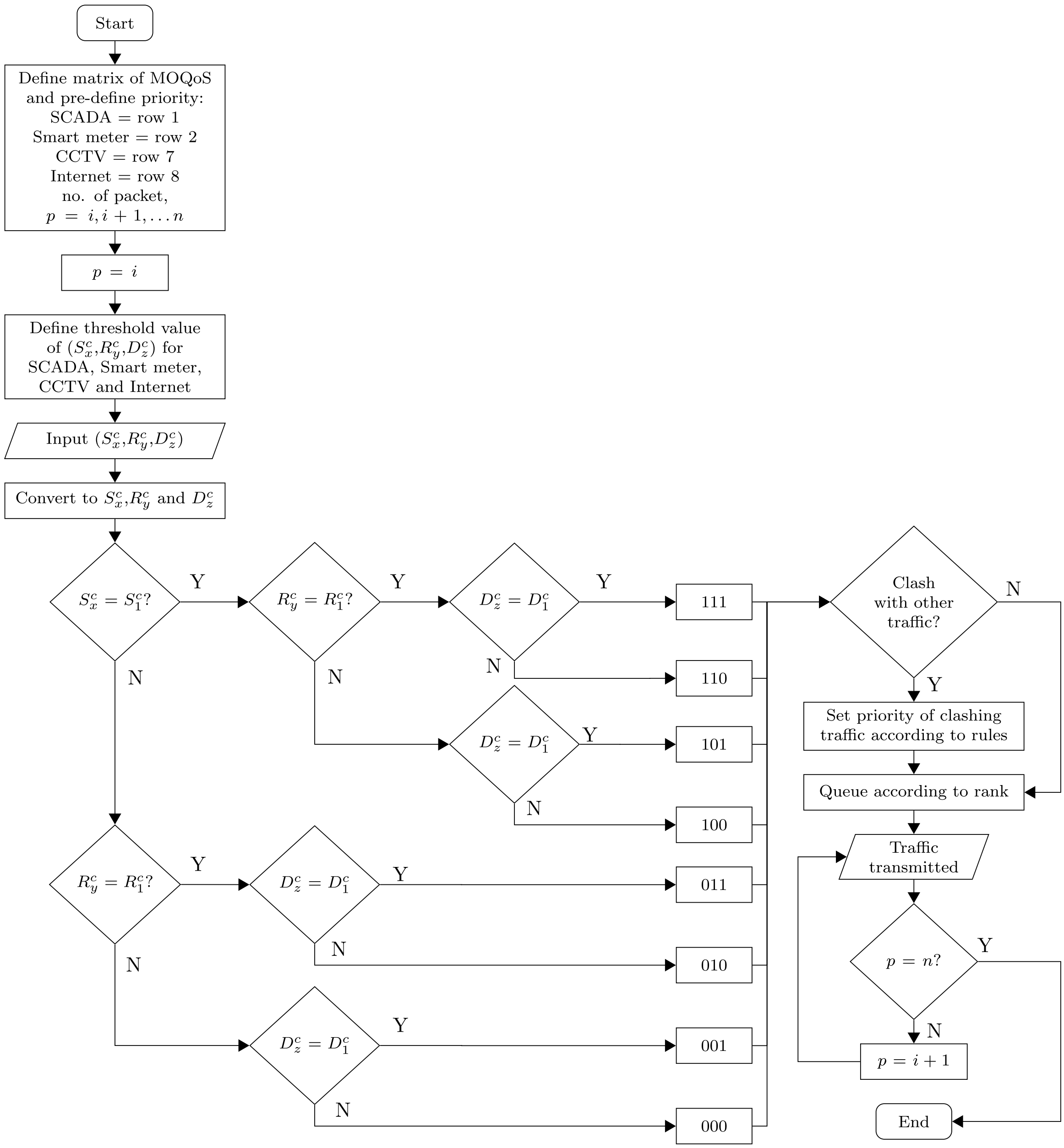


FIGURE 1. Detailed flow chart of context aware traffic scheduling (CATSchA) algorithm.

IV. CONTEXT AWARE TRAFFIC SCHEDULING (CATSchA) ALGORITHM

The CATSchA algorithm is placed in an ingress MPLS router containing three experimental (EXP) bits traffic in the Shim header. The EXP bits allow mapping up to 2^3 possible combinations. SCADA, SM, CCTV, and Internet traffic types are evaluated based on the three parameters represented in the EXP bits, i.e., data size, data rate, and delay.

A. MATRIX OF QOS (MOQOS)

Figure 1 schematizes the flow of CATSchA algorithm. To develop the CATSchA algorithm, a matrix, known as the Matrix of QoS (MOQoS), is first defined. MOQoS has eight rows and five columns, as shown in Figure 2. This matrix comprises three EXP bits, one "types of traffic" bit and one "rank" bit in each of its columns. The three EXP bits comprising data size, data rate, and delay are located in columns 1, 2, and 3, respectively; "types of traffic" is placed in Column 4; and "rank" is placed in Column 5.

The three EXP bits are represented by binary, as shown in Table 4. The "types of traffic" is classified as 1 for SCADA, 2 for SM, 3 for CCTV, 4 for the Internet, and 0 for other traffic. The "rank" is divided into eight levels, where 1 is the highest rank and 8 is the lowest.

TABLE 6. Summary of parameters used for inequality comparison.

Traffic	Default Priority	Default Rank	Parameters for Inequality Comparison								
			Data Size, S_x			Data Rate, R_y			Delay, D_z		
			Inequality	Priority	Rank	Inequality	Priority	Rank	Inequality	Priority	Rank
SCADA	111	1	Any	111	1	Any	111	1	Any	111	1
SM	110	2	>	**0**10	6	>	0**0**0	8	≥	00**0**	8
									<	00**1**	7
						≤	1**1**0	6	≥	01**0**	6
									<	01**1**	5
			≤	**1**10	2	>	1**0**0	4	≥	10**0**	4
									<	10**1**	3
						≤	1**1**0	2	≥	11**0**	2
									<	11**1**	1
CCTV	001	7	≥	**0**01	7	≥	0**0**1	7	>	00**0**	8
									≤	00**1**	7
						<	0**1**1	5	>	01**0**	6
									≤	01**1**	5
			<	**1**01	3	≥	1**0**1	3	>	10**0**	4
									≤	10**1**	3
						<	1**1**1	1	>	11**0**	2
									≤	11**1**	1
Internet	000	8	≥	**0**00	8	≥	0**0**0	8	≥	00**0**	8
									<	00**1**	7
						<	0**1**0	6	≥	01**0**	6
									<	01**1**	5
			<	**1**00	4	≥	1**0**0	4	≥	10**0**	4
									<	10**1**	3
						<	1**1**0	2	≥	11**0**	2
									<	11**1**	1

$$Matrix\ of\ QoS = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 2 & 2 \\ 1 & 0 & 1 & 0 & 3 \\ 1 & 0 & 0 & 0 & 4 \\ 0 & 1 & 1 & 0 & 5 \\ 0 & 1 & 0 & 0 & 6 \\ 0 & 0 & 1 & 3 & 7 \\ 0 & 0 & 0 & 4 & 8 \end{bmatrix}$$

FIGURE 2. Matrix of QoS (MOQoS).

Meanwhile, the priority rank is displayed in rows from 1 to 8. The traffic priorities ranks are predefined as $S_1\ R_1\ D_1, S_1\ R_1\ D_0, S_0\ R_0\ D_1$ and $S_0\ R_0\ D_0$ for SCADA, SM, CCTV, and Internet equivalent to row 1, 2, 7, and 8, respectively.

After the MOQoS has been defined, threshold values of $S^C_{threshold}, R^C_{threshold}$ and $D^C_{threshold}$ are defined because they are required for inequality comparison to later produce the output of the three EXP bits context aware priority.

B. INEQUALITY COMPARISON FOR INPUT PARAMETERS

The incoming data size, S^C_n, incoming data rate, R^C_n and previous delay D^C_n of each traffic type are analyzed. These input values are converted into binary forms for inequality comparison. Both threshold values and input parameters must undergo inequality comparison to determine the priority ranking of each traffic type.

The three input parameters are then compared with their threshold requirements to set priority ranking for SM, CCTV, and Internet based on inequality comparison, as shown in Table 6. SCADA is exceptional because it has the highest priority rank. Moreover, its input parameters do not undergo inequality comparison although its threshold parameters have been defined. This is because SCADA forms the virtual brain of the power automation system as it receives data and information in real-time from each substation for supervisory control and remote configuration. Thus, the priority of SCADA cannot be compromised by any possible situations. In contrast, the priorities of the other three traffic types are ranked based on inequality comparison between their input parameters and threshold values.

The first decision-making is performed in terms of data size, S_x, followed by data rate, R_y, and delay, D_z. Both data size and data rate comprise values from the current cycle, i whereas, the delay value is obtained from the previous cycle, $i-1$. Data size is chosen as the first parameter for inequality comparison because it is the most influential factor for determining traffic transmission, which also affects the delay.

Columns 2 and 3 of Table 6 summarize the default priority and default ranking for each traffic type, respectively. Rank is denoted by three bits, which ranks from the highest priority (111, rank 1) to the lowest priority (000, rank 8). These three bits of packet header represent the input parameters, i.e., data size, data rate, and delay, respectively, as denoted in bold in Table 6.

SCADA will always have the highest priority and will be ranked as 1 because of its crucial application; thus, its rank remains unchanged throughout the CATSchA algorithm. If the input is higher than the threshold, it is denoted as ">", and if the input is lower than the threshold, it is denoted as "<"; both these values are denoted by bits 0 and 1, respectively.

C. RULES FOR CLASHING CASES

After the traffics are ranked, CATSchA algorithm will check for any clash among them. There are certain conditions where SCADA, SM, Internet or CCTV are having the same priority with each other after inequality comparison process. In case of such events, the following rules are applied:

1) If the priority of newly defined traffics, $P_{i,j}^{new}$ other than the priority of SCADA, $P_{1,1}^{SCADA}$ is ranked as 1 (111), $P_{i,j}^{new}$ is demoted to rank 2 (110) because rank 1 is reserved only for SCADA. This can be observed in Equation (1).

$$P_{i,j}^{new} = \begin{cases} P_{i,2}^{new} & ; P_{i,j}^{new} = P_{1,1}^{SCADA} \\ P_{i,j}^{new} & ; P_{i,j}^{new} \neq P_{1,1}^{SCADA} \end{cases} \tag{1}$$

where i represents the traffic type ($i = 1, 2, 3, 4$); j denotes the rank number ($j = 1, 2, 3, 4, 5, 6, 7, 8$) and P indicates priority of a particular traffic. If newly defined ranking of $P_{i,j}^{new}$ is not the same as $P_{1,1}^{SCADA}$ therefore, $P_{i,j}^{new}$ can maintain in its new rank directly.
For example, in cases involving CCTV, $P_{3,1}^{new}$ desires for rank 1; however, rank 1 is permanently reserved for SCADA, $P_{1,1}^{SCADA}$. According to Equation (1), CCTV is demoted to rank 2, i.e., $P_{3,2}^{new}$, which is its newly defined ranking. However, if CCTV desires for rank 8, rather than rank 1, then it can directly acquire $P_{3,8}^{new}$ as its newly defined ranking.

2) Furthermore, if rank 2 (110) is also occupied by another traffic, the existing traffic, $P_{i,j}^{exist}$ is ranked according to $P_{i,j}^{new}$ predefined priority. Thus, $P_{i,j}^{new}$ is assigned rank 2 as its newly defined priority, as shown in Equation (2).

$$P_{i,j}^{new} = \begin{cases} P_{i,2}^{new} & ; P_{i,j}^{new} = P_{i,2}^{exist} \\ P_{i,j}^{new} & ; P_{i,j}^{new} \neq P_{i,2}^{exist} \end{cases} \tag{2}$$

where $P_{i,2}^{exist}$ represents the existing traffic available in rank 2 and $P_{i,j}^{new}$ denotes the demoted traffic from rank 1, which desires to occupy rank 2. $P_{i,2}^{new}$ indicates the newly defined ranking of the demoted traffic that is positioned in rank 2. If there is no existing traffic in rank 2, then $P_{i,j}^{new}$ can directly occupy rank 2. Otherwise, if $P_{i,j}^{new}$ is assigned a rank other than rank 2, then it can stay in that position, as shown in Equation (3).

$$P_{i,j}^{exist} = \begin{cases} P_{i,pre-defined}^{new} & ; P_{i,2}^{new} = P_{i,2}^{exist} \\ P_{i,2}^{exist} & ; P_{i,2}^{new} \neq P_{i,2}^{exist} \end{cases} \tag{3}$$

where $P_{i,pre-defined}^{new}$ signifies the existing traffic in rank 2 that is taking over the predefined ranking of $P_{i,2}^{new}$ as its new rank in the event of $P_{i,2}^{new}$ conquering rank 2. Otherwise, $P_{i,2}^{exist}$ remain at its rank when there is no other traffic attempting to have rank 2 as its new priority rank.
For example, the demoted CCTV, $P_{3,2}^{new}$ clashes with SM, $P_{2,2}^{exist}$, which is the existing traffic on rank 2. According to Equation (2), CCTV has the right to stay in rank 2, $P_{3,2}^{new}$ as its newly defined ranking. Meanwhile, SM takes the predefined ranking of CCTV, $P_{2,7}^{new}$ as its newly defined ranking according to Equation (3). However, if SM is positioned in rank 8, $P_{2,8}^{exist}$, then CCTV can directly take over rank 2 as $P_{3,2}^{new}$.

3) In general, if two traffic types encounter the same rank between rank 2 and rank 8 without attempting to occupy rank 1 (SCADA), the higher rank of the predefined traffic, $P_{i,j}^{new(1)}$ is going to possess the newly defined ranking. The lower rank of the predefined traffic, $P_{i,j}^{new(2)}$ will give up its desired new rank by taking over the predefined rank of $P_{i,j}^{new(1)}$ as its newly defined ranking. This is shown in Equation (4).

$$P_{i,j}^{new} = \begin{cases} P_{i,j}^{new(1)} & ; P_{i,j}^{new} = P_{i,j}^{new(1)} \\ P_{i,pre-defined}^{new(1)} & ; P_{i,j}^{new} = P_{i,j}^{new(2)} \end{cases} \tag{4}$$

where $P_{i,j}^{new}$ represents the two input traffic types that are clashing, $P_{i,j}^{new(1)}$ denotes the higher rank traffic and $P_{i,j}^{new(2)}$ signifies the lower rank traffic. $P_{i,pre-defined}^{new(1)}$ indicates the predefined ranking of the higher rank traffic, $P_{i,j}^{new(1)}$ when the input traffic belongs to lower ranked traffic.
For example, in cases wherein both SM, $P_{2,7}^{new(1)}$ and Internet, $P_{4,7}^{new(2)}$ attempt to occupy rank 7. According to Equation (4), SM should occupy rank 7, $P_{2,7}^{new(1)}$ as its newly defined ranking; meanwhile, Internet occupies the predefined ranking of SM $P_{4,2}^{new(2)}$ as its newly defined ranking.

4) If three traffic types have the same rank between rank 2 and rank 8, in which one of the traffic is the existing traffic in the rank, the higher rank of the predefined traffic, $P_{i,j}^{new(1)}$ will possess the newly defined ranking. The lower rank of predefined traffic $P_{i,j}^{new(2)}$ gives up its desired new rank by taking over the predefined rank of $P_{i,j}^{new(1)}$ as its newly defined ranking. Moreover, the existing traffic, $P_{i,j}^{exist}$ will take over the predefined rank of $P_{i,j}^{new(2)}$ as its newly defined ranking. The two clashing traffic types are solved using Equation (4), whereas the existing traffic in that position is solved as in Equation (5).

$$P_{i,j}^{exist} = \begin{cases} P_{i,pre-defined}^{new(1)} & ; P_{i,j}^{exist} = P_{i,j}^{new(1)} \\ P_{i,pre-defined}^{new(2)} & ; P_{i,j}^{exist} = P_{i,j}^{new(2)} \end{cases} \tag{5}$$

where $P_{i,j}^{exist}$ represents the existing traffic that occupied a certain rank desired by the other two traffic types. $P_{i,j}^{new(1)}$ denotes the higher rank traffic and $P_{i,j}^{new(2)}$ signifies the lower rank traffic. $P_{i,pre-defined}^{new(1)}$ specifies the predefined ranking of higher rank traffic, $P_{i,j}^{new(1)}$ as newly defined ranking for the existing traffic. Meanwhile, $P_{i,pre-defined}^{new(2)}$ indicates the predefined ranking of the lower rank traffic, $P_{i,j}^{new(2)}$ as newly defined ranking for the existing traffic.

For example, in cases wherein SM, $P_{2,7}^{new(1)}$, Internet, $P_{4,7}^{new(2)}$ and CCTV $P_{3,7}^{exist}$ desire to occupy rank 7. According to Equation (4), SM should occupy rank 7, $P_{2,7}^{new(1)}$ as its newly defined ranking; meanwhile, Internet occupies the predefined ranking of SM, $P_{4,2}^{new(2)}$, rank 2 as its newly defined ranking. According to Equation 5, CCTV will take over the predefined ranking of Internet, $P_{3,8}^{exist}$, rank 8 as its newly defined ranking.

After clashes between the traffic types have been resolved, a new priority is set for each traffic type that will decide its rank in queuing for packets before the transmission begins. If there are no changes in the characteristics of each traffic type, then both its priorities and ranks will be the same as the predefined value. In contrast, if there are changes in the characteristics of each traffic type, then both its priorities and ranks will be set to a new one.

Then, the traffic will follow a step to queue the packets according to their newly defined priorities and ranks, which are reflected in MOQoS because the matrix needs to update its content for each traffic type before its transmission.

Lastly, traffic is transmitted based on its priorities and ranks. Input values are the important factors that mainly influence the traffic ranks corresponding to its priority; these values are in charge of controlling the transmission time of each traffic type. The algorithm performance is evaluated in terms of delay, throughput, and link efficiency, as discussed in the following section.

V. PERFORMANCE EVALUATION

The algorithm is evaluated via simulation in Network Simulator 3 (NS-3), version 3.18. NS-3 is used as a simulation platform because it is a discrete-event network simulator, which is suitable for research and development [18].

A. DESIGN MODEL

Figure 3 illustrates the network topology implemented in NS-3 using eight nodes. The topology used is tree topology. Three nodes are configured as routers, namely R1, R2, and R3; four nodes serve as hosts for source comprising PC1, PC2, PC3, and PC4; the remaining node functions as a host for the destination, namely PC5. Such a topology is created to mimic the real topology used in the utility network but with simpler network design for proof of concept.

Table 7 shows the default parameter values used in the CATSchA algorithm. The link capacity of the network is 100 Mbps to emulate the real amount of data transmission in a utility environment. The cycle time is 2 ms to ensure the size of each packet is fixed to 1024 Bytes throughout the simulation to accurately evaluate the performance parameters. The maximum number of packets is kept at 50 in the queue for transmission to cater for a high number of queued packets in each router.

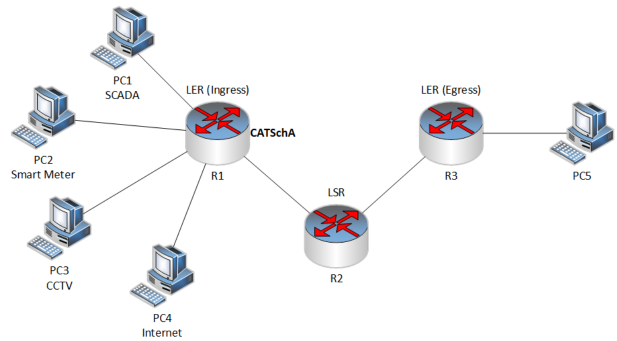


FIGURE 3. CATSchA algorithm in tree topology.

TABLE 7. Default parameters used in the CATSchA algorithm.

Default Parameters	Values
Link capacity	100 Mbps
Cycle time	2 ms
Packet size	1024 Bytes
Maximum packets in the transmission queue	50

Four incoming traffic types, i.e., SCADA, SM, CCTV, and Internet, are represented by PC1, PC2, PC3, and PC4 respectively; these traffic types are pumped into a router, R1. Packets of each traffic are transmitted from R1 into a destination host, PC5, over intermediary nodes, R2 and R3.

B. SIMULATION RESULTS

To demonstrate the advantages of the CATSchA algorithm, it is compared with an algorithm without context aware based on processor sharing using the same design parameters. Results are measured in terms of delay and throughput using the following four different cases:

- Case 1 (priority from high to low: SCADA → SM → CCTV → Internet)
- Case 2 (priority from high to low: SCADA → SM → Internet → CCTV)
- Case 3 (priority from high to low: SCADA → CCTV → SM → Internet)
- Case 4 (priority from high to low: SCADA → Internet → CCTV → SM)

1) VALIDATION

This section discusses the validation of the CATSchA algorithm to assure that the coding is designed and correctly functioning before its performance is evaluated. The CATSchA algorithm simulated in NS-3 is compared with simulation via MATLAB in terms of traffic ranking, as shown in Table 8. The result shows that the ranking of output traffic between NS-3 and MATLAB are similar. This proves that the context aware program for the CATSchA algorithm is correct and thus validated.

2) DELAY

Delay is defined as the time taken for a packet to traverse from source to destination. The lower the delay, the better will be

TABLE 8. Validation results between NS-3 and MATLAB.

		Input Traffic				Output Traffic							
						NS-3				MATLAB			
		1 SCADA	2 SM	3 CCTV	4 Internet	1	2	3	4	1	2	3	4
1	Data Size	Any	0	0	0	SCADA	SM	CCTV	Internet	SCADA	SM	CCTV	Internet
	Data Rate	Any	1	0	0								
	Delay	Any	0	1	0								
2	Data Size	Any	1	0	0	SCADA	SM	Internet	CCTV	SCADA	SM	Internet	CCTV
	Data Rate	Any	1	0	0								
	Delay	Any	0	0	0								
3	Data Size	Any	1	1	1	SCADA	CCTV	SM	Internet	SCADA	CCTV	SM	Internet
	Data Rate	Any	1	1	1								
	Delay	Any	0	0	0								
4	Data Size	Any	0	1	0	SCADA	Internet	CCTV	SM	SCADA	Internet	CCTV	SM
	Data Rate	Any	0	1	0								
	Delay	Any	0	0	0								

the performance of an algorithm. To evaluate the performance of the CATSchA algorithm, offered load is varied from 0 to 100 Mbps with 10 Mbps step to observe their delay variations. Full offered load of 100 Mbps is used to emulate the real amount of data transmitted in a utility environment [19]. Figures 4a–4d show the delay results for all cases in the tree topology, where four different traffic types are considered during simulation.

The solid lines show the results of the proposed CATSchA algorithm, whereas the dotted lines show results of an algorithm implemented without context awareness. As the offered load for all traffic increases from 0 to 100 Mbps, the delay for the CATSchA algorithm linearly increases. However, when the context aware algorithm is not applied, the delay of all traffic steadily increases up 90 Mbps; then, a sudden hike occurs because a large number of packets is transmitted from source to destination.

As shown in Figure 4a, the delay of all the traffic is improved using the CATSchA algorithm because the traffic is queued based on its context aware priority; thus, SCADA packets are transmitted first before considering SM, CCTV, and Internet packets. Each traffic type has its specific allocated transmission time as has been set in the CATSchA algorithm; therein, SCADA packets are transmitted first followed by SM, CCTV, and Internet. This differs from the case of the algorithm without context aware, which grants the packets for transmission based on predefined priority and number of packets. Each traffic type transmits its packets with the same transmission time.

When low-priority traffic needs to be treated with urgency, the CATSchA algorithm can dynamically change the priority based on its context. Such a situation happens in Case 2 (Figure 4b), where the priorities for Internet and CCTV are swapped. The graph shows that the Internet has lower delay compared with Case 1, wherein at full load, the delay reaches only up to 3.1 s as opposed to 4 s in Case 2. In contrast, for CCTV, the delay increases up to 3.9 s when the priority is set to a lower level.

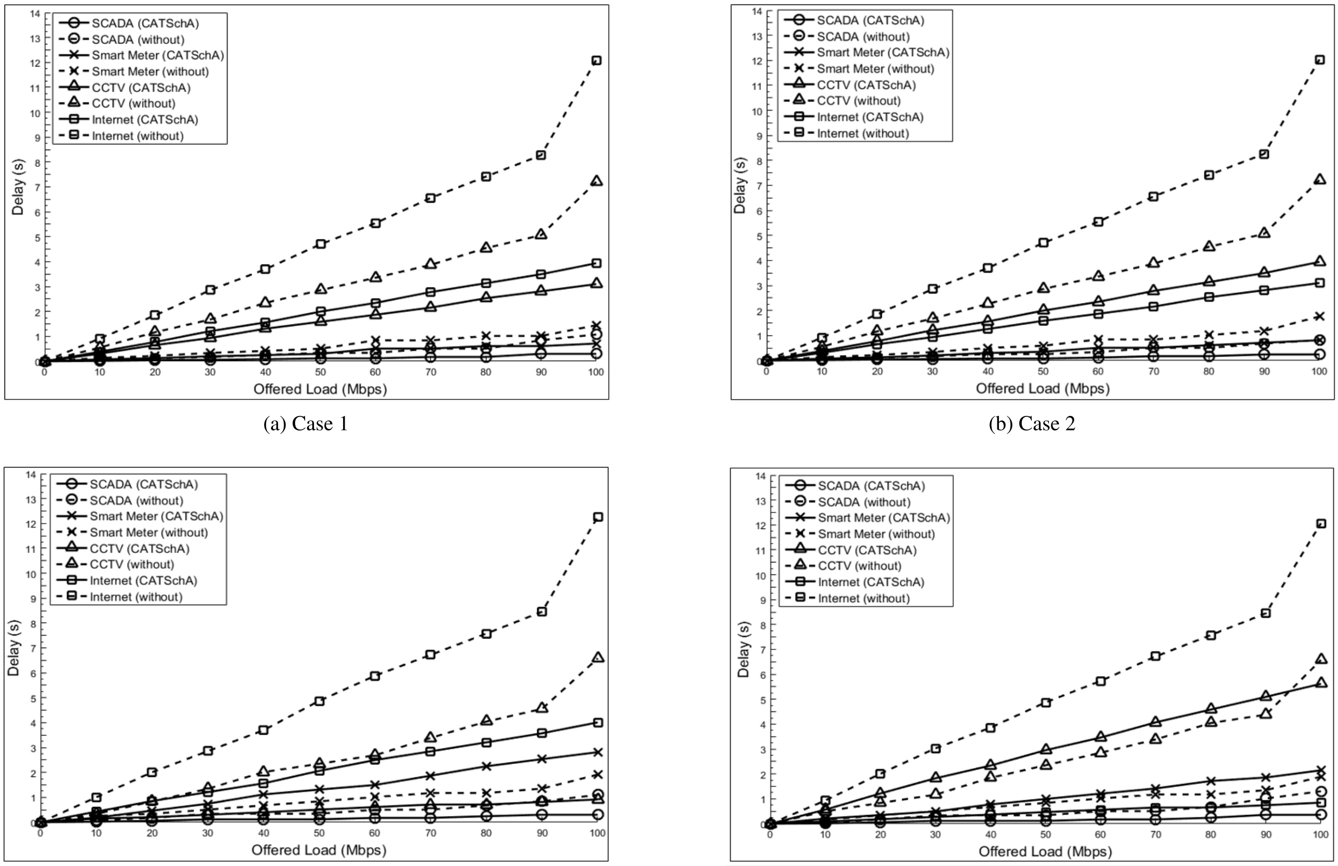
The context aware feature can also be observed in Case 3 (Figure 4c), where CCTV has a higher priority compared to SCADA and SM. SCADA, CCTV, and Internet have improved their delays using the CATSchA algorithm compared with the algorithm without context aware. However, with the CATSchA, it apparent that SM has a higher delay compared to when context aware is not implemented. SM with CATSchA algorithm is expected to have a longer delay because its priority ranking is demoted from rank 2 to rank 7. Thus, SM packets in the CATSchA algorithm have been queued based on its newly defined ranking, where SCADA packets are transmitted first, followed by CCTV, SM, and Internet packets.

SM data has a higher delay, as observed in Case 4 (Figure 4d), when it needs the least priority. SCADA, Internet, and CCTV have improved their delays using the CATSchA algorithm. However, SM has a higher delay when it uses the CATSchA algorithm; the offered load increases from 0 to 100 Mbps and the delay reaches up to 3.83 s compared to 2.2 s when context aware is implemented. This is due to its context awareness, where its newly defined ranking (rank 8) is higher than its predefined ranking (rank 2). It is expected for SM with the CATSchA algorithm to have longer delay compared with the algorithm without context aware because its priority ranking is demoted from rank 2 to rank 8. Therefore, the packets of SM are queued as the last traffic to be transmitted. Regardless of the expected increment in the delay of SM, this is deemed acceptable as the priority is served according to its situation. When there is no urgency for some data to be transmitted at the time, the priority of transmission may be given to some traffic that have higher urgency to cater to the QoS and SLA.

In general, using the CATSchA algorithm, the lowest priority data may suffer compounding additional delay because it needs to wait for higher priority traffic to be transmitted first. This is expected in strict priority scheduling, and it is necessary for the algorithm to guarantee its context awareness.

3) THROUGHPUT

Throughput is defined as the amount of data transferred between source and destination to show the performance



(a) Case 1 (b) Case 2

(c) Case 3 (d) Case 4

FIGURE 4. Delay versus offered load for CATSchA algorithm and that without context aware in tree topology.

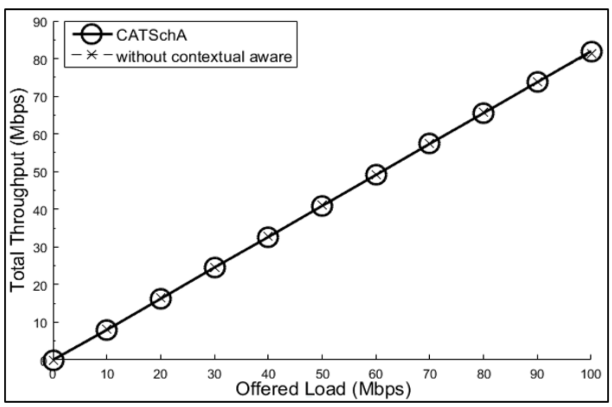


FIGURE 5. Throughput versus offered load for CATSchA algorithm and that without context aware in tree topology.

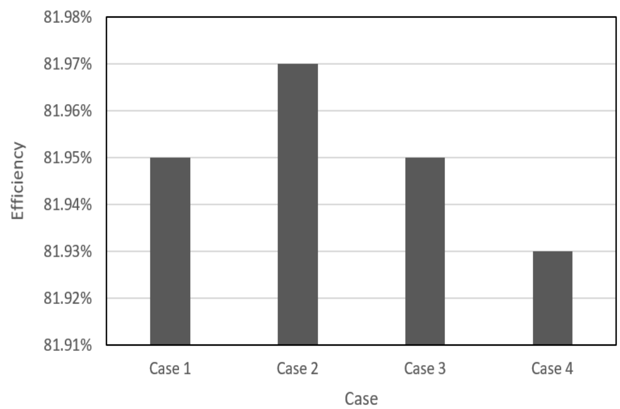


FIGURE 6. Throughput versus offered load for the CATSchA algorithm and that without context aware in tree topology.

between the CATSchA algorithm and that without context aware. SCADA, SM, CCTV, and Internet require a high amount of throughput or must at least maintain the same throughput as the algorithm without context aware.

Figure 5 shows the total throughput results, where four different traffic types are considered during simulation. Results show that the traffic trends are similar for both the CATSchA algorithm and that without context aware from 0 until it reaches the full offered load. This is because the amount of data transferred for each traffic between source and destination is similar. Furthermore, both the algorithms use the same design parameters that include link capacity of 100 Mbps, cycle time of 2 ms, packet size of 1024 Bytes and 50 maximum packets in the transmission queue. This observation is expected; thus, the CATSchA algorithm improves the delay without using context aware but maintains a high throughput.

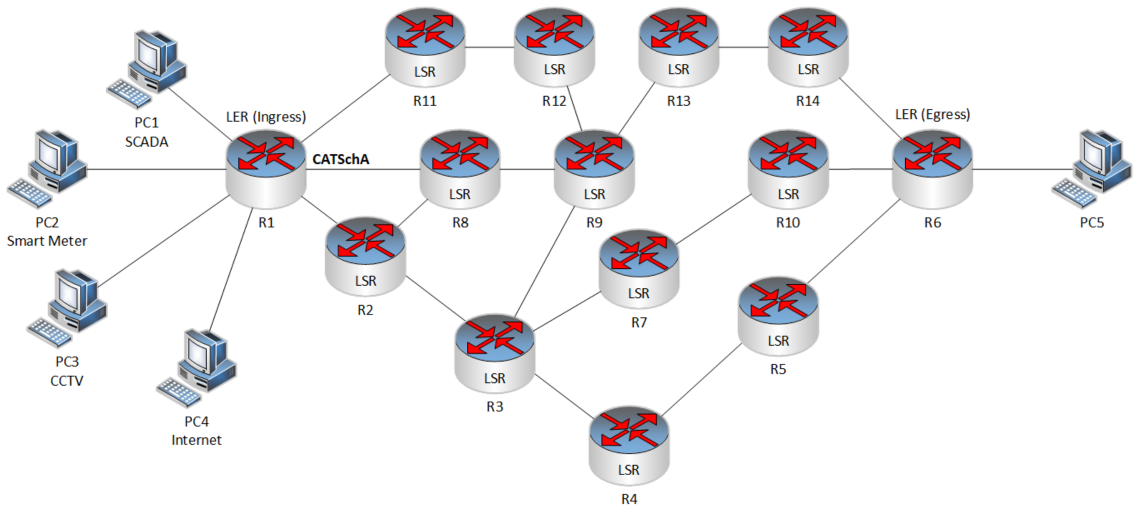


FIGURE 7. CATSchA algorithm in mesh topology.

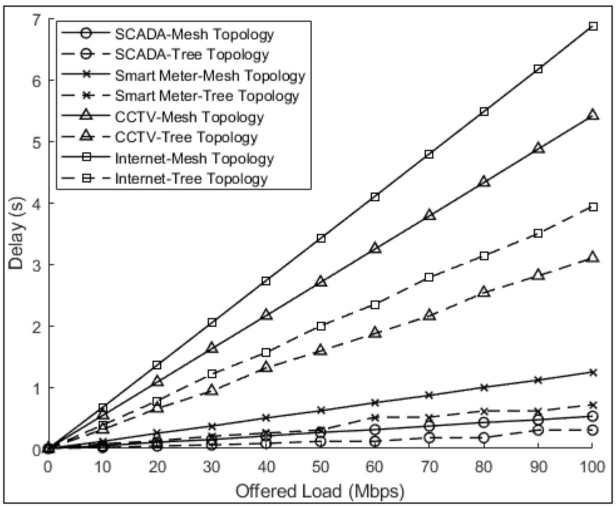


FIGURE 8. Delay versus offered load for tree and mesh topologies.

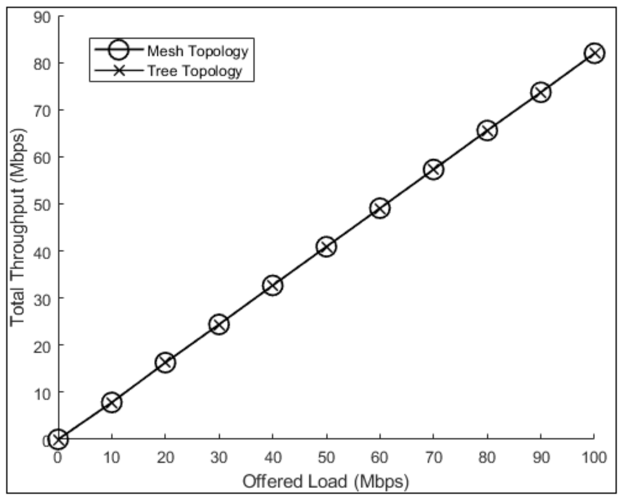


FIGURE 9. Throughput versus offered load for tree and mesh topologies.

4) LINK EFFICIENCY

Link efficiency is defined as the quality of throughput or data transferred between source and destination as it reflects the performance of CATSchA algorithm. The higher the throughput, the better will be the link efficiency of the algorithm. The link efficiency E_{ff} is obtained in Equation (6) [20].

$$E_{ff} = \frac{Thr_{total}}{Link\ capacity} \times 100 \tag{6}$$

where Thr_{total} denotes the total throughput of SCADA, SM, CCTV, and Internet at full load divided by the link capacity of the network; link efficiency is obtained in terms of percentage by 100 Mbps times 100.

Figure 6 shows the link efficiency from Case 1 to Case 4, where four different traffic types are considered during simulation at 100 Mbps offered load using the CATSchA algorithm. Thus, using the CATSchA algorithm, a stable link efficiency can be obtained, i.e., 81.95 ± 0.02%.

C. SCALABILITY OF ALGORITHM

To further test the algorithm in a different topology and test its scalability, mesh topology is used in Figure 7. The effects on the algorithm's throughput and delay are also studied using NS-3. 14 nodes are configured as routers from R1 to R14, where four nodes serve as hosts for source and one node serves as host for the destination.

Figure 8 shows the delay results of mesh topology for Case 1, where tree topology is also plotted on the same graph for comparison. It is evident that the trend of the graph for all the cases are the same, with the same context aware priority where SCADA is having the shortest delay, followed by SM, CCTV, and Internet. However, the delay for mesh topology is now longer, where it increases as high as 75%

on average. Considering the case of Internet as an example, at full load, the tree topology has a delay of 3.94 s, whereas the mesh topology has a delay of 6.87 s. This is expected because the data need to travel longer routes and with more hops to reach from a source to a destination. An additional delay of 75% for addition of at least three hops that the data need for transmission concludes that the approach is indeed computationally cost-effective. This is because the CATSchA algorithm is only placed inside ingress label edge router, and not in all label switched router, to save its processing time.

Figure 9 presents the throughput results of mesh topology for Case 1, together with the tree topology. It shows the same throughput utilization, indicating that there is no tradeoff of the throughput although a greater number of hops and different topology are used.

VI. CONCLUSION

We successfully characterized power distribution traffic types based on their dynamically varying environmental contexts. We also demonstrated a context aware-based traffic scheduling algorithm, known as the CATSchA algorithm, in a power distribution network. The CATSchA algorithm considered the QoS and the traffic priorities to adapt to the varying power network conditions, fully optimizing the available resources. The context aware part of the algorithm using NS-3 was validated using MATLAB; results revealed that both methods agreed well with each other. The proposed algorithm was then compared with conventional traffic scheduling algorithms without context aware. Simulations were performed using NS-3, wherein four cases were tested by varying the priority of each traffic type. Results showed notable improvements in the delay maintaining high throughput and link efficiency. Scalability test of the algorithm, wherein the CATSchA algorithm was tested in a more complicated topology proved that the trend of the delay was the same although the delay value showed an expected and acceptable increment. Throughputs of the CATSchA algorithm between mesh and tree topologies also agreed with each other. Thus, the proposed algorithm improved the overall performance of power distribution network by prioritizing traffic based on their contexts and traffic requirements without having to neglect any packet. With optimal resource utilization, efficient energy consumption can be achieved, which could be explored in future research.

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