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SDN-based Quality of Service Networking for Wide Area Measurement System

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Abstract*-- Wide Area Measurement System (WAMS) infrastructure is one of the most significant elements of the smart grid which measures, collects, and analyzes data in the power system. Fundamental components of the WAMS are Phasor Measurement Units (PMUs), Phasor Data Concentrators (PDCs) and its relevant applications. The PDC collects data from several different PMUs, integrates data and sends it to the control center. In order to achieve a stable implementation of WAMS, the communication structure should be reliable and meets the Quality of Service (QoS) requirements for various applications in the network. In this paper, we propose a novel WAMS communication infrastructure by utilizing the Software Defined Networking (SDN) technology, which can enhance the reliability of the corresponding networks. In the proposed model, in order to meet the applications QoS needs, the traffic flows are categorized into different class of services, and then by applying a QoS mechanism, along with a content-aware queuing algorithm, the maximum capacity for the critical traffic is obtained. This provides a low latency for critical WAMS applications. The proposed model has been implemented in the Mininet environment using the Ryu Controller. The implementation results indicate that the proposed infrastructure reduces end-to-end delay and packets loss and utilizes the network resources optimally.

***Index Terms*— Wide Area Measurement System (WAMS), Phasor Measurement Units (PMUs), Software Defined Networking (SDN), Smart Grid, Active Queue Management (AQM)**

I. Introduction

Online monitoring plays an important role in controlling smart grid reliability. Online monitoring needs communication infrastructures in order to provide information with very low latency for smart grid applications. Current Supervisory Control and Data Acquisition (SCADA) does not fulfill this necessity and has to be improved. Many companies have switched to more advanced systems called Wide Area Measurement System (WAMS) instead of using the SCADA system to overcome this drawback [1-2] which can increase the efficiency of modern power systems where synchronous data is sent online with a high rate. In the WAMS system, the Phasor Measurement Units (PMUs) receive information from the buses and send it to the PDCs. PDCs aggregate the received data, and then send it to the control centers [3-4]. PMUs measure current, voltage, phase and frequency of the power grid. This information would be accessible to various applications for monitoring, control, and other purposes.

These applications require low packet delays and end-to-end delay bound. Correct operation of these applications can increase the reliability of WAMS networks and prevent failure in the network. For example, PMU data should be sent to the control center with minimal delay, otherwise, it may result in failures in the smart grid. Accurate and global view from the entire network are required to avoid these sorts of problems and satisfy the application requirements. A global view to the network is hardly achieved in the current network structure.

On the other hand, the emerging concept of Software-Defined Networking (SDN) can provide a global view of the entire network for integrated resource management [5-6]. The SDN makes it easier for network operators to evolve network capabilities. In SDN, the control plane is separated from data plane which makes network management and policy management easier than traditional networks [7-8].

In this paper, we propose a new software based infrastructure which uses SDN to meet the QoS requirements of WAMS applications. In the proposed infrastructure, the QoS routing and context-aware queuing management are developed to meet flow requirements.

The contributions of the current study can be summarized as follows:

- Using SDN infrastructure in WAMS and applying its capabilities to meet the quality of service requirements. The WAMS requires a global network view to provide end-to-end quality of service requirements. On the other hand, all switches should be logically managed and configured centrally. In order to provide both requirements, SDN infrastructure has been used so that the best path for each PMU is obtained, and then switches are configured dynamically to provide the required bandwidth of each PMU. In order to increase network reliability, a backup path is also selected for each PMU.
- A novel context-aware Active Queue Management (AQM) is proposed that improves the delay performance of PMU flows in the WAMS networks. The idea behind the stated method is to drop less important packets (packets containing older data). As a result, available bandwidths are allocated to high priority packets (packets containing newer data), which provides optimal use of network resources and increases the reliability of WAMS. In WAMS network, the most recent data belonging to any PMU accurately describes the network states and has higher priority than older data.
- A new algorithm for setting PDC timer is presented. When PDC receives a new timestamp, it waits to receive data from other PMUs. This action increases the latency of PMU packets. In the proposed algorithm, to set PDC timer, the maximum end-to-end delay between PDC and PMU is taken into account.

The remainder of this paper is organized as follows. The

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related work is described in section II. The proposed architecture and QoS mechanism are presented in Section III. The performance of the proposed model is evaluated in section IV. Finally, Section V gives the concluding marks of the paper.

II. Related work

Due to the importance of quality of service in WAMS networks, many articles have been reviewed this area and proposed various solutions. Generally different QoS requirements such as delay and reliability are considered to meet the required levels of QoS classes.

The communication network infrastructure in smart grid consists of a home area network (HAN), neighborhood area network (NAN), and wide area network (WAN). Many methods have been proposed to provide QoS-aware routing protocols in NAN networks. Providing QoS in a wireless NAN is a challenging task because there will be a large number of smart meters and sensors within a dense urban area but bandwidth is limited and transmissions are not reliable.

There are many ways to provide QoS on NAN networks [9]. Many methods try to provide the quality of the requested service by changing the channel access scheme [10-13]. In these methods, the channel allocation mechanism is performed based on packets' priorities. This requires a change in MAC layer. For example in [11], the authors have introduced a new medium-access approaches that is based on delay-estimation and data-prioritization procedures that are performed by the application layer to satisfy the delay requirements of the smart-grid application. Furthermore, in [12], an Adaptive Quality of Service scheme (AQoS) and an Adaptive Guaranteed Time Slot (GTS) allocation scheme (AGTS) for IEEE 802.15.4-based WSNs is proposed. The AQoS reduces the delay by adaptively modifying the GTS based on applications' requirements. In addition, in this paper, more time slots are given to sensor nodes with high priority data.

On the other hand, traffic specifications should be considered in order to provide QoS requirements. For example in [14], authors propose a new QoS-aware routing protocol to be used in NAN networks. In this method, some parameters such as data size and transmission rate are considered to meet QoS requirements for various applications. In addition to improve the reliability of the network, multi-gateway backup routing scheme is used. As a result, when a link fails, packets will be transmitted through an alternate path.

In some papers, cognitive radio wireless sensor networks is used to enhance the overall network performance by dynamic spectrum access and, hence, improve spectrum utilization in smart grid environments [15-17].

The related works mentioned above do not take into account the different structure of the WAMS. In order to provide QoS, the WAMS structure must be considered. For example, in some methods, optimal method for locating PMUs has been used to reduce delays. In [13], a method for aggregator placement in a NAN is presented which is based on the density of nodes and meets QoS requirements. The authors have examined the minimum concentrator density required to meet various QoS requirements in terms of packet delay, packet error probability, and node outage probability. In [18] a distributed algorithm to minimize the data aggregation latency under the physical interference mode has been proposed, which jointly considers routing, power assignment and transmission scheduling.

In all the methods outlined above, only NANs are considered, thus, cannot guarantee end-to-end delays. In order to provide quality assurance in smart grids, the proposed algorithm should be suitable for use in all parts of the network. Various methods have been proposed for this purpose.

In some other articles, the use of multicast to minimize the end-to-end delay for WAMS communications. [19-21]. Updating the multicast group in these methods creates a lot of overhead and it is inapplicable for real-time applications.

HetGrid propose a multipath routing mechanism by employing end-to-end physically disjoint paths [22]. To meets the strict QoS requirements of Smart grid applications, it employs Source Routing-based QoS Routing (SRQR) and Compensative Multi-Routing (CMR) mechanisms. In this method to obtain a fault-tolerant communication system for the critical applications, use of physically-disjoint redundant paths between each pair by using the constructed overlay network. In LOES [23], authors proposed a local optimization emergency scheduling scheme, which uses a self-recovery for large-scale IoT-based smart grid to improve the real-time performance of the emergency data packets and reduce the hop counts and distance between distributed source nodes and sink nodes.

Due to the lack of global view in current network structure, none of the above methods can guarantee end-to-end delays but using SDN, this problem has been solved. Many articles have used SDN to provide QoS [24-25]. In [25], author proposed SUDOI (SDN for ubiquitous data center optical interconnection) architecture for heterogeneous cross-stratums and multi-layer networking modes, by introducing a service-aware schedule scheme. This model implements cross-stratum optimization of applications and optical networks, to meet the QoS requirement of extensive user access. It can be used only in data center communication network and can't guarantee the maximum end to end delay.

Some papers have tried to calculate the maximum end to end delay in the network using network calculus [26-27]. In [26] authors have proposed two network models for the provisioning of real-time QoS with SDN. The first model, the multi-hop model (MHM), assigns a rate and a buffer budget to each queue in the network. In this model, packet loss is possible due to the lack of buffer consumption. The second model, the threshold-based model (TBM), fixing a maximum delay for each queue in the network. In this article, using a network calculus, a deterministic model of the network is provided. [27] propose a SDN-based QoS networking approach that maintains an accurate network model. This approach is accurate by deterministically modeling resource (bandwidth, buffer) allocation and QoS parameter (delay budget) allocation through network calculus. This approach use of novel function split between routing and resource allocation for achieving hard real-time QoS required by industrial communication based on SDN. In these methods, authors do not consider dynamic flow requirements in WAMS.

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Due to the increase in the number of PMUs in today's smart power grids, traffic sent by PMUs consumes large amounts of network resources. This could disrupt the functionality of the various applications in the network while in the design of the communications infrastructure for WAMS, it is necessary to meet the requirements of different applications [28-30]. Some of these requirements are specified as follows:

Dynamic data priority changes: One of the important issues in the WAMS network is the nature of its data in comparison to the data of other networks. In WAMS, newer data have higher priority than older data and this should be considered in network routing policies. For example, the data received from the Bus has a different priority. If this data has changed more than a certain amount, it can indicate the probability of an error in the generators, thus they must be transferred with a higher priority than the data that has not been changed.

High sensitivity to delay: One of the important components of WAMS are the applications and each of these applications has different QoS requirements. For example, applications for network analysis need to be sent securely, monitoring applications need to send data over time and are more latency-insensitive, or distribution automation, outage alarming and load control signaling require very low latency. Meeting the requirements of different applications has also an important role in increasing the reliability of the system. Any failure in providing these requirements leads to serious consequences and generate extra costs.

Networks with different transmission structures and media: WAMS is basically a large-scale network that consists of a variety of networks within, including different transmission media such as copper wiring, optical fiber, power line carrier technologies, and wireless technologies. These networks may be controlled by different controllers. Thus, the QoS algorithms in WAMS should be scalable and take into account the different characteristics of all different transmission media.

III. PROPOSED ARCHITECTURE AND MODEL

The communication infrastructure of WAMS is different from the communication infrastructure of traditional networks. In WAMS, some data is only useful when it is received within a specified time-slot and is useless if its delay is exceeded than a certain value. We have used SDN infrastructure in our proposed approach (Fig. 1). SDN helps the WAMS infrastructure to adjust some parameters in order to meet the QoS requirements of different applications.

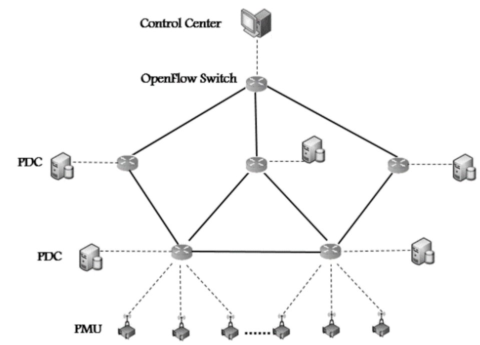

Fig. 1. The propose architecture

Communication and PDC processing delay are two important factors that cause delay in WAMS networks. To reduce the total delay in the network, both mentioned delay should be reduced. Delay caused by communication network is related to the network operations such as routing or waiting time in the queues. In order to reduce this delay, two main operations are proposed. In the proposed model, we initially, classify the existing flows and allocate network resources to higher priority flows based on the new QoS algorithm. Then by using the queuing management algorithm, the packet's waiting time in the queues is reduced. We also propose a new algorithm to adjust the PDC timer that reduces the PDC processing time.

a) QoS class of services

In the proposed model, we consider two traffic classes namely Normal and QoS0, between each PMU and PDC. The PMU data are classified and assigned to Qos0 service class. We also define three different traffic classes, QoS1, QoS2 and Normal between each PDC and the control center where QoS1 class has higher priority than QoS2 and Normal. Note that at each PDC, the Normal traffic passes without any changes, while QoS0 traffic may be mapped to QoS1 or QoS2, based on the content of its data. For example, when the voltage or current of a device exceeds a specific threshold, a circuit breaker must be opened immediately, otherwise it will cause instability of the power network, or even damage the network device. The PMU data belonging to this event should be sent to the control center quickly, so this data mapped to QoS1 class. The QoS2 class has a lower priority than QoS1 and is less delay-sensitive. This information is used to analyze system behavior or archive system information. The PMU data belonging to this class should be sent to the control center as possible and can be processed later. The Normal traffics belongs to information that does not meet specific requirements and are sent upon available bandwidth. As mentioned earlier, the data sent by the PMUs categorized in class QoS0. The data belonging to this class only exists on the path between PMUs and PDCs (Figs. 2).

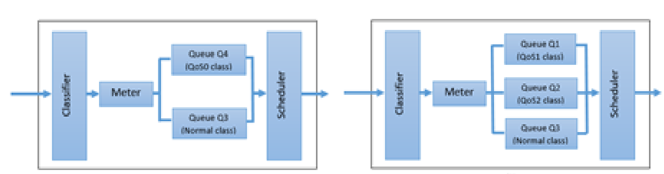

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Fig. 2. Switch architecture: a) between PMU and PDC b) between PDC and control center

b) *Proposed routing algorithm*

The PMU must be registered in PDC. The PMU, in form of CFG1, sent its information and capabilities to the PDC. When the switch receives the first packet (CFG1) form PMU will not know the route to follow to a destination, it attaches the packet into a Packet_In message and then sends it to the controller for determining the path. The Path_Selection API computes the least-cost path to the PDC based on bandwidth and delay. The Path_Selection API for computing bandwidth requirement use of data information in CFG1 packet. Then QoS_Rule_Setting module sends Meter table and Flow table setting to the involved switches in the path. When the path is established, the subsequent packets be forwarded throughout the network without consulting the SDN controller. Then Resource_Monitor update the switch and link resource.

The modules are described below:

Flow_Monitor: This module is implemented as a Deep Packet Inspection (DPI) module. The purpose of this module is to detect the type of packets. When a packet is sent from the switch to the controller, this unit detects the type of packet (Control, Data...) and extracts the necessary information. This information is used for use in other modules.

Resource_Monitor: This module is responsible for updating the residual resources of switches and links. When a switch is connected to the network, its data is sent to the controller in the message header. This module stores the switch information and its links in the database. This information is provided to the network module to use this information for routing. Using this information, an overview of the network is available. After selecting the path by the Path_Selection module, the sources used by the links and switches are updated. If the switch connector is disconnected, all routes that it uses are re-routed and the network's communication structure is updated. This improves the reliability of the network against error.

QoS_Rule_setting: The task of this module is to apply the necessary switch settings. These settings are sent to switches using OF-CONFIG commands. When the bandwidth required for the path is specified, this module guarantees the amount of bandwidth needed along the path by setting Max_Ratio and Min_Rate to all the switches involved in the path. By setting the parameter Min_Rate in each switch, that switch tries to provide at least the same amount of its port to this route. If the Min_Rate property is set, the switch will prioritize this queue (and any flow forwarded via this queue) to achieve the mentioned minimum rate, at the cost of other flows rates.

Path_Selection: The purpose of this function is to find the shortest path considering the resource constraints. Based on the bandwidth required by the PMU, this function selects the shortest path that has the requested bandwidth. Routing is done according to the network structure. The network structure can be modeled as graph G= (V, E), where V is the set of switch and E is the set of the links interconnecting the switches. Let |V|=n and |E|=m represent the number of switches and the number of the links, respectively. This graph connects PMUs to PDCs. Let S_r, S_c, C and L_r represent the remaining switch resource, resource consumption of each switch, link cost and the remaining resources, respectively. Resource consumption of each switch is also denoted by L_c.

The following optimization model has been suggested to find the optimal route:

$$\min\{c_p \mid p \in P \; and \; S_c^p \leq S_r^p , L_c^p \leq L_r^p\} \quad (1)$$

where L_c^p , L_r^p, S_c^p and S_r^p represent the link consumption resources, remaining link resources, switch consumption resources and remaining switch resources for path p, respectively. The proposed optimization model is an Integer Linear Program (ILP) problem and is therefore, NP-hard. As a polynomial time solution for these problems, LARAC [31] method can find the best path which is based on Lagrange's method. Initially, the model is rewritten in the following form [31]:

$$\min\{c(p) \mid p \in P \; and \; v(p) \leq \Delta_p\} \quad (2)$$

where c(p) is the cost of entire path p, which is the same as C_p, $v(p)$ is total consumed resources (including switch and link) and Δ_p is a total remaining resource of path p.

The main idea of Lagrange's method is to eliminate restrictions by bringing them into the objective function:

$$L(\mu) = \min\{c_\mu(p) \mid p \in P\} - \mu\Delta_p \quad (3)$$

Lagrangian function can be described as:

$$L(\mu) = c_\mu(p_\mu) - \mu\Delta_p \quad (4)$$

For any value of the Lagrangian multiplier μ, $L(\mu)$ is a lower bound on the optimal objective function value of the original problem. To calculate the sharpest possible lower bound, the following model should be solved, which is referred to as the Lagrangian multiplier problem:

$$L^* = \max\{L(\mu) \mid \mu \geq 0\} \quad (5)$$

The main issue for solving the above model is how to search to determine the optimal value of L and determine the search stop condition. Algorithm1 which is based on LARAC method is proposed to find the optimal value of L.

Algorithm 1 Solve Model.

```
Function LARAC(s,t,c,v,Δ)
Begin Function
p_c = Dijkstra(s,t,c)
If v(p_c) ≤ Δ_p then
    Begin
        Return p_c
    End
P_v = Dijkstra (s,t,v)
if V(p_v) > Δ_p than
    Begin
        return There is no solution
    End
Repeat
    Begin
        μ = (c(p_c)−c(p_v)) / (v(p_v)−v(p_c))
        R = Dijkstra(s,t, c_μ)
```

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```
        If cμ(r) = cμ(pc) then
            Begin
                Return pv
            End
        If V(r) ≤ Δp then
            Begin
                Pv = r
            End
        Else pc = r
    End Repeat
End Function
```

First, the model is computed by set μ =0, so the shortest path is calculated without considering the resource constraints. If the found path meets resource constraint, this is the optimal path, and the algorithm stops. Otherwise, the path is stored as the best path that does not satisfy resource constraint, called P_c. Then the algorithm looks for another path with respect to resource constraints, denoted as P_v. If there is no path with the desired conditions, there will be no answer to this problem and the algorithm stops. Otherwise, the algorithm continues with the calculation of the value of $\mu = \frac{c(p_c)-c(p_v)}{v(p_v)-v(p_c)}$

For a certain value of u, if $c_\mu(r) = c_\mu(P_c) = c_\mu(P_v)$, the optimal value of u is found; otherwise, the value of P_c or P_v is replaced by r according that r satisfies or does not satisfy the constraints. Routing between PDC and control center is also done with the above algorithm.

For each PMU, in addition to the main path, an alternative backup path is also selected. To select the backup path, an algorithm similar to the main path selection algorithm is used. In the proposed model, not to let the main path and the backup paths to have shared links, the cost of the main route links is set to a large number.

c) Proposed queuing method

PMUs measure synchrophasors and time-stamp them with a time source such as the Global Positioning System (GPS), as per the synchrophasor standards. (IEEE 1344, IEEE C37.118)[32-33]. The synchrophasor applications use this time-synchronized data to time-align the voltage and current time series to be used for analysis and having coordinated activity over a wide geographical area.

Newer data has higher priority for WAMS applications and provides more accurate information about the network conditions. On the other hand, due to the limited capacity of the queues, in some cases the removal of packets is unavoidable. Therefore, it is better to delete older packets in the queue. In the proposed algorithm, this problem is considered in order to the manage queues performance. Four individual queues, Q= {Q_1, Q_2, Q_3, Q_4} are set for different traffic classes= {QoS1, QoS2, Normal, QoS0}, respectively (Figs. 2). Due to the differences in the characteristics of each service class, each queue has a different queue management algorithm.

In the existing active queuing management methods, traffic management is made based on the local information of each switch, which can lead to a reduction in the network utilization. Due to lack of a global network information, more packet may be dropped. If global network information is available, traffic can be routed through the best available paths. In the proposed model, using the SDN infrastructure, the global information of the network is available, so this information can improve the queue management algorithm and enhance the performance of the network. When network congestion is detected, the proposed model attempts to send traffic from alternative paths instead of dropping the packets. As a result, this leads to efficient use of network resources and avoids more packet loss. Each queue has its own queuing active management mechanism. The proposed queue management algorithm is described below.

Queue management of QoS1 traffic class (Q1 queue): As mentioned earlier, the traffic imported into this queue has the highest priority. Packets belonging to this category of network flows should be sent with the least delay. These packets are PMU data and should be sent to the control center quickly. Note that the other queues should not be served as long as this queue has a packet. The queue management algorithm for Q1 queue is such that if the queue length is greater than threshold TR, then the rerouting operation is performed, and if the queue length is greater than threshold TH, then the packet drop operation is performed (Algorithm 2). Each of these operations is described below:

-Rerouting: When the queue length exceeds TR, this algorithm performs routing for specific flow. Selecting the proper flow for rerouting is done based on the Counter field in the flow table. This field represents the number of packets sent by each stream. In this algorithm, a flow that has the lowest value is selected and then the backup path is chosen for it.

- Packet dropping: Packet drop is based on the packet time field and is done when the queue size is greater than threshold TH. As previously stated, the data received by the PMU is tagged with the timestamp and then is transmitted. This timestamp specifies the time the packet is sent. Given this, if there are multiple packets of the same flow in the queue, the packets with a newer label have more priority than other packets. In the DROP function, the older packets are selected to be dropped. To create fairness between flows, the Select_Flow function choses the appropriate flow to drop the packet of it. The flow is chosen based on the following function [34]:

$$p = 1 - \frac{B_f}{R_0} \quad (6)$$

where B_f is the fair share, and R_0 is the average transfer rate of the flow. B_f can be calculated using the Counter field. The flow that has the highest value of p is selected.

Algorithm 2 Q1 active queue management.

```
Function Enqueue (p):
  #A new packet p of flow F is received ;
  Len=Queue_Length()
  if Len < TR then
      put p at the end of the queue
  else if Len > TR and Len < TH then
      sel_flow=Select_min_flow()
      reroute(sel_flow)
      put p at the end of the queue
  else if Len > TH then
      f=Select_Flow()
      packet=Select_first_packet(f)
```

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```
        drop(packet)
        put p at the end of the queue
   end if
End of Function
```

Queue management of QoS2 traffic class (Q2 queue): The QoS2 packets enter Q2 queue. Priority of Q2 queue is less than Q1 queue and is greater than the Q3 queue. To manage this queue, similar to Q1 queue, two thresholds TR and TH are used. When the queue length exceeds TR, a flow is randomly selected and the flow rate is decreased. If the queue length exceeds the value of TH, then the packet drop operation is performed (Algorithm 3). Each of these methods are described as follows:

- Flow rate reduction: Flows in Q2 queue belong to PDCs. The data rate of PDC is almost constant. When Q2 queue length exceeds TR, this function randomly selects a flow and requests the corresponding PDC to reduce its flow transmission rate. The PDC reduces its transmission rate once receives this message for a period of time.

-Packet dropping: This function acts similar to the previous function in Q1 active queue management.

Algorithm 3 Q2 active queue management.

```
Function Enqueue (p):
   #A new packet p of flow F is received ;
   Len=Queue_Length()
   if Len < TR then
        put p at the end of the queue
   else if Len > TR and Len < TH then
        sel_flow=Select_rnd_flow()
        reroute(sel_flow)
        put p at the end of the queue
   else if Len > TH then
        packet=Select_first_packet()
        drop(packet)
        put p at the end of the queue
   end if
End of Function
```

Queue management of Normal traffic class (Queue Q3): Traffics other than PMU and PDC traffics are considered as the background traffics and are forwarded to this queue. We have used the RED algorithm [35] as an active queue management.

Queue management of QoS0 traffic class (Queue Q4): This queue contains PMUs` traffics. This queue is available on all switches between PMUs and PDCs. The data transmission rate of each PMU is fixed. Suppose there are *n* PMUs connected to a PDC. Let data rate of each PMU is set to B_i. As a result, the value of the service rate for all switches can be calculated as follows:

$$\text{Min\_Rate} = \sum_{i\in N} B_i \qquad (7)$$

Using this value, the data rate required by queue Q4 is computable. By setting the Min_Rate value by equ (7), the service rate required by each PMU is guaranteed. Note that Min_Rate is the minimum output port capacity that the switch will provide to the queue.

d) PDC timer setting

Each PDC activates a timer by receiving a new timestamp and waits to receive data from other PMUs. This action increases the latency of PMU packets. PDC timer has a fixed value for all PDCs in the network. Dynamic setting for this timer towards the lowest value will reduce the latency of PDC packets. On the other hand, each PMU can be connected to a PDC with different media and the delay experienced by PMU packets can be vary at different times. Consequently, if the timer is not set to the correct value, it may cause a high delay (If the specified value is higher than the maximum latency of connected PMU), or we may miss some packets at the control center, (If the specified value is less than the maximum latency of connected PMU). So, in the proposed method, the timer value depends on the network conditions. To set the timer at each PDC correctly, Algorithm 4 is used. The DelayGet application calculates the end-to-end latency between each PMU and PDC in specified time intervals. Then, maximum calculated latency is considered as the timer value for the next time interval.

Algorithm 4 PDC timer setting.

```
Function Timer_Setting ():
   #A new time interval ;
   # Di (Delay of PMU i)
   DelayGet()
   Timer(T) = Max(Di)
   New_Timer= Min( α * Timer(T) + β * Timer (T-1), Threshold)
   Timer(T)= New_Timer
End of Function
```

To apply the proposed method in the real power grid system, we just need to upgrade the communication infrastructure to support SDN. Due to use of SDN infrastructure, the network switches should be OpenFlow switch and require the installation of a controller in the network. Note that we don't need to modify the PDC and PMU hardware or software. As we mentioned earlier, the only option that needs to be in the PDC is to set the timer dynamically. When the PDC receives a data message from multiple PMU, it should first align the frame according to their time stamps. Each PDC waits for a maximum wait time to reach the data of all the PMUs and then aggregate them (i.e. 1-4 seconds). This waiting time is fixed in current WAMS network, but in the proposed method, in order to reduce the delay in the network, it needs to be varied according to the network conditions. This reduces end-to-end delay. PMUs can be used without any modification.

IV. Simulation Results

In this section, we evaluate the performance of the proposed model using Mininet [36] and the Ryu [37] controller. The simulation architecture is shown in Fig. 3. Simulation platform is equipped with a Corei7 CPU system with 8GB RAM. The channel bandwidth is set to 1MB/s. The simulation parameters are given in Table 1.

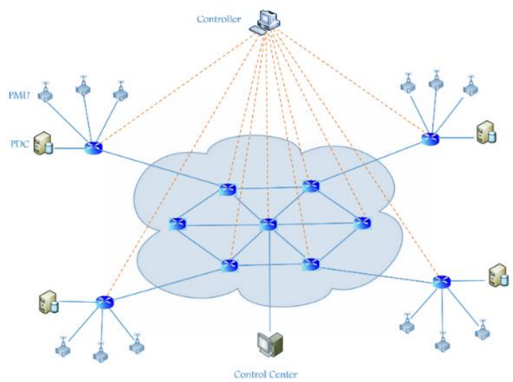

Fig. 3. Simulation architecture

Table 1. Simulation parameters

SDN-based WAMS	Value
OS	Ubuntu 14.04.02 LTS
RAM	8GB
Cpu	Corei7
OpenFlow	Ver 1.3
Mininet	Ver 2.3.0d1
Ryu	Ver 4.11
Network Setting	Value -Count
PMU	12
PDC	4
Bandwidth	1MB
Switch	11

Simulation is performed in four different scenarios. The QoS parameters are evaluated firstly. Different traffic flows are injected into the network with different bandwidths and the results are investigated. In the first scenario, QoS parameters such as jitter, drop count, and the allocated bandwidth to each traffic class are evaluated.

In the second scenario, the fairness of the proposed mechanism under different traffic classes is investigated. In this scenario flows from class QoS1 are only considered. The purpose of this scenario is to investigate fairness in jitter, drop count and allocated bandwidth.

In the third scenario, the impact of the proposed model on delivery rate for different applications is investigated, and finally, in the last scenario, the performance of the proposed model for determining the value of the PDC timer is evaluated.

A. Scenario1: Evaluation of QoS parameters

In this scenario we inject traffic flows from different traffic classes within a test period of 150 seconds. Normal traffic exists over a period of 150 seconds. The QoS2 and QoS1 traffics are injected in the network during time interval 25-125 and 50-100, respectively. Having the above mentioned scheme, three different experiments with different traffics are performed. In the first experiment all flows of Normal, QoS1, and QoS2 traffic classes have the same requested bandwidth equal to 300KB/s. So, the total bandwidth of all traffic classes is equal to 900 KB/s which is less than the available bandwidth. As shown in Fig.4, the proposed model allocates the requested bandwidth to all traffic classes. Fig. 5 shows the jitter value for all traffic classes. It is clear that the jitter value for QoS1 and QoS2 classes is very low. For Normal traffic, at time t=50 s, where the QoS1 traffic is injected which needs more processing, the jitter value increases.

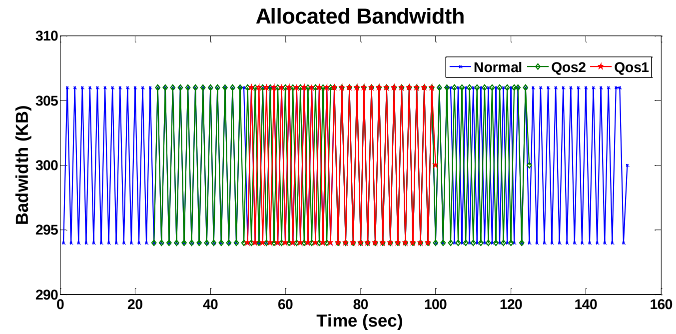

Fig. 4. Scenario1 (experiment 1): Allocated bandwidth

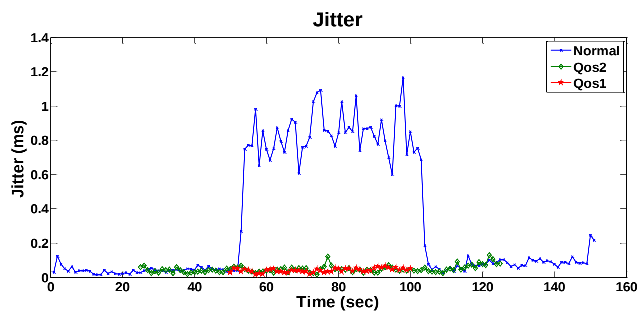

Fig. 5. Scenario1 (experiment 1): Jitter values of all traffic classes

In the second experiment, the total traffic is more than available bandwidth. In this experiment, the requested bandwidth for each class is equal to 600KB/s. As shown in Figs.6-8, up to time t=25 seconds, there is only Normal traffic in the network. As a result, the amount of jitter and drop count are almost equal to zero and the allocated bandwidth is equal to the request bandwidth, but at time t=25s, upon arrival of QoS2 traffic, the jitter and the drop count of the Normal traffic increases and only 400KB/s (out of 600KB/s) is allocated to this class. This is because the total requested traffic (1200KB/s) is greater than the available bandwidth (1000KB/s). Note that the priority of QoS2 traffic is more than the priority of Normal traffic. At time t=50s, upon arrival of QoS1 traffic, the jitter and the drop count of QoS2 and Normal traffic increases. Also, the allocated bandwidth to these two classes decreases. The reason is that, the priority of QoS1 is higher than the priority of the other classes.

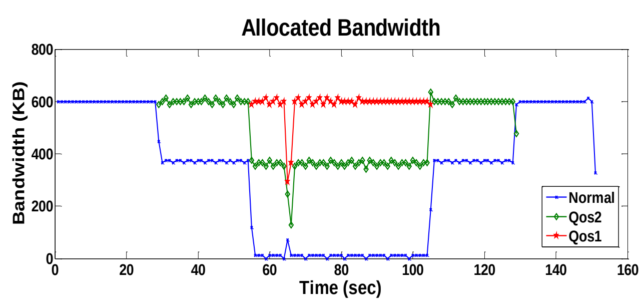

Fig.6. Scenario1 (experiment 2): Allocated bandwidth

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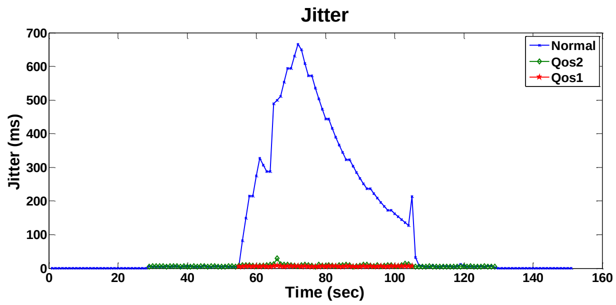

Fig. 7. Scenario1 (experiment 2): Jitter values of all traffic classes

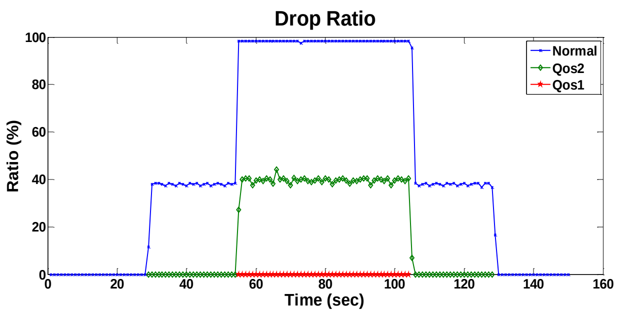

Fig.8. Scenario1 (experiment 2): Drop ratio

In the third experiments, the requested bandwidth of each traffic class is set to 1000KB/s which is equal to the available bandwidth. The results are shown in Figs. 9-11. In time period [50-100], because of the presence of QoS1 traffic, bandwidth is not available for the other traffics, so the amount of jitter and drop count of other traffics are greatly increased. In time period [25-50] and [100-125], where there is not any QoS1 traffic, all bandwidths are given to QoS2 class because it has higher priority than Normal traffic class.

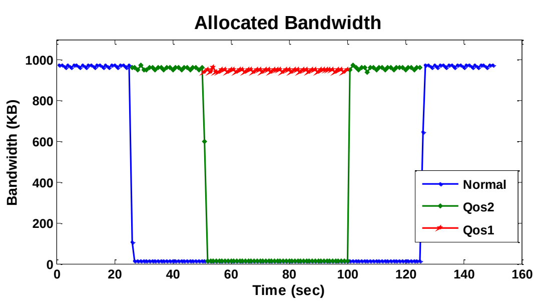

Fig. 9. Scenario1(experiment 3): Allocated bandwidth

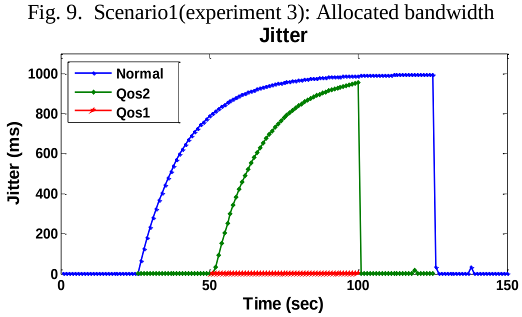

Fig. 10. Scenario1 (experiment 3): Jitter values of all traffic classes

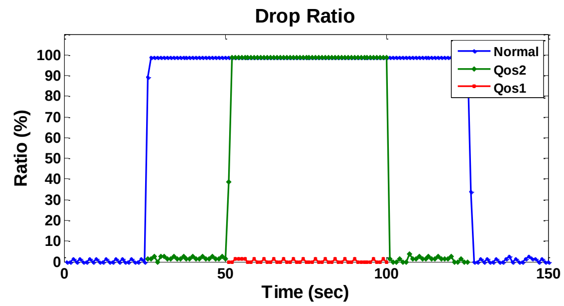

Fig. 11. Scenario1 (experiment 3): Drop ratio

B. Scenario Two: Fairness evaluation

In this scenario, the fairness of proposed model is evaluated where QoS1 traffic class is only considered. The fairness of the proposed model is compared with MPLS [38] method. We consider four different QoS1 traffic flows each needs 300KB/s bandwidth. In Figs. 12-13, the allocated bandwidth to each flow is depicted. In the MPLS routing, if there isn't enough network resource all new requests will be rejected without considering the fairness. In this method, the input packets are dropped if the queue is full. This causes unfairness between flows and also decreases network utilization. Unlike the MPLS, in the proposed approach, network resources are shared between all traffic classes and packet drop is performed based on the allocated bandwidth to each class. As a result, fairness is provided between different traffic flows.

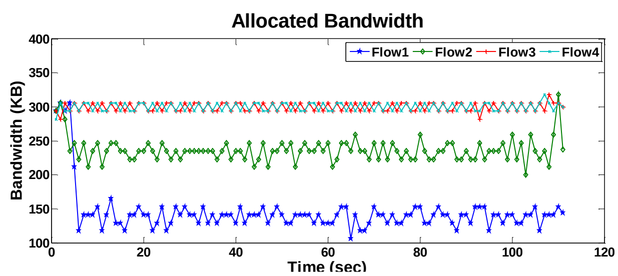

Fig. 12. Scenario2: Allocated bandwidth (MPLS)

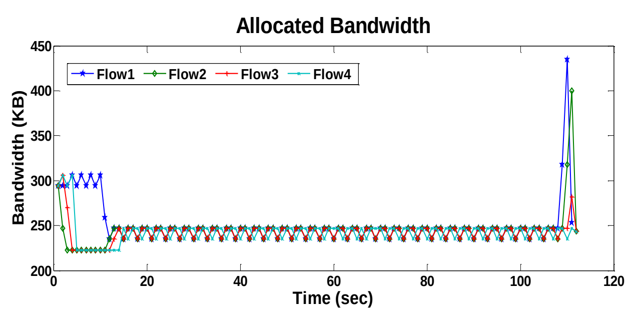

Fig. 13. Scenario2: Allocated bandwidth (proposed model)

In Fig.14, the jitter value of all traffic flows by applying the MPLS method, is shown. It can be seen that this approach is unable to provide the equal jitter for all traffic flows. In Fig.15, the jitter values provided by the proposed model is shown. It is clear that as all traffic flows have the same priority (QoS1), the jitter value is almost the same for all of them.

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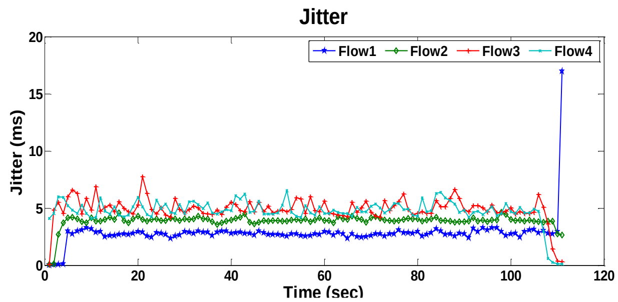

Fig. 14. Scenario2: Jitter (MPLS)

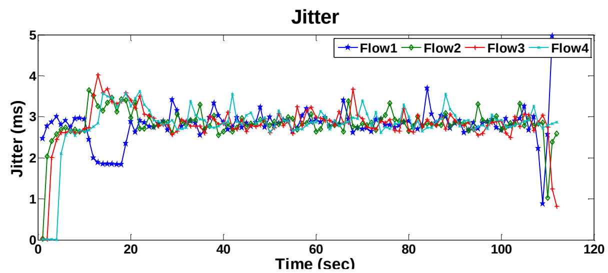

Fig. 15. Scenario2: Jitter (proposed model)

In Figs.16-17, for both methods, the drop rate is plotted versus simulation time. It can be seen that unlike the MPLS, the proposed model can provide the same packet drop rate for all traffic flows.

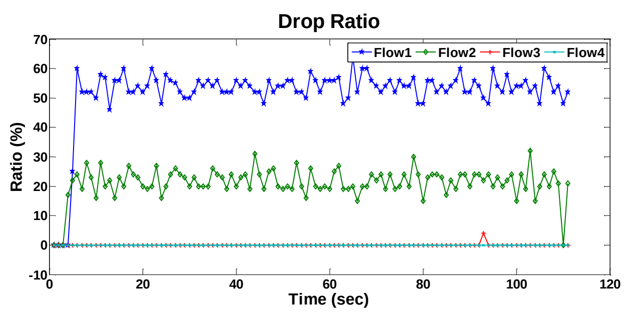

Fig. 16. Scenario2: Drop ratio (MPLS)

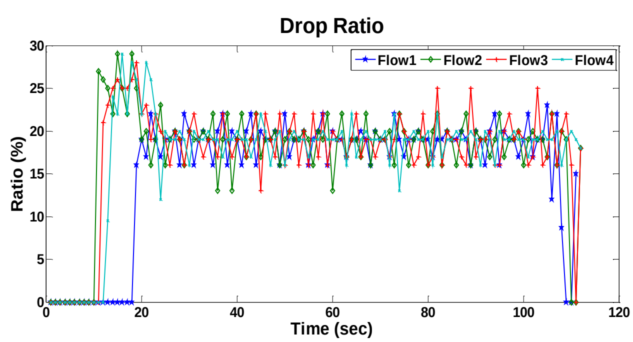

Fig. 17. Scenario2: Drop ratio (proposed model)

C. *Scenario Three: Packet delivery rate evaluation*

In this section, the FNET/GridEye [39] Dataset is used to evaluate the performance of the proposed model. FNET/GridEye is a low-cost, quickly deployable GPS-synchronized wide-area frequency measurement network. High dynamic accuracy Frequency Disturbance Recorders (FDRs) are used to measure the frequency, phase angle, and voltage of the power system. For example, the data of a PMU is shown in Figure 18.

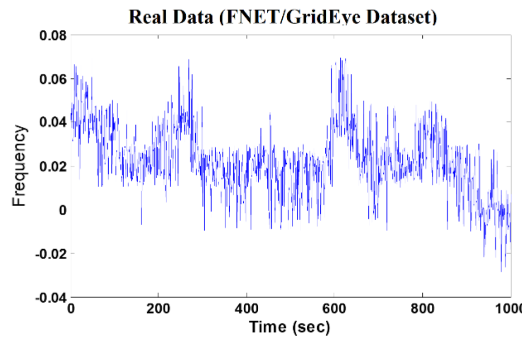

Fig. 18. Scenario3: Real Data (FNET/GridEye Dataset)

PMU data whose value is greater than 0.01 is considered as QoS1 Class while the other data belonging to each PMU is considered as QoS2 Class. In Figure 19, for both QoS Classes, the latency of PMU data is shown. As it can be seen, the proposed approach provides very low delay for QoS1 class. This is because this data is classified to QoS1 Class and sent with a high priority.

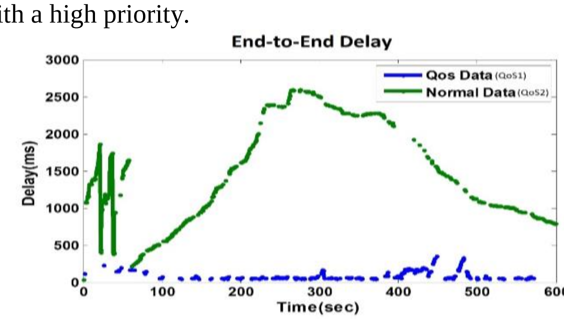

Fig. 19. Scenario3: delay (Qos vs Normal data)

In next scenario, the impact of the proposed model on the delivery rate of different applications is analyzed. As already mentioned, reliability is one of the important factors in the WAMS. The higher delivery rate shows the higher performance of the routing algorithms and queue management. In this scenario, different applications are considered to evaluate the packet delivery rates. Each application has a different end-to-end threshold. To compare the efficiency of the proposed model, we have implemented HetGrid [22] and MPLS on the SDN platform. Table 2 shows the package delivery rate of the proposed method, HetGrid and MPLS. In the proposed model, packet delivery rates is higher than HetGrid and MPLS approach. This confirms the high accuracy and reliability of the proposed routing and queue management algorithm. This is because in the proposed model, using the efficient routing and the queuing management algorithms, packet drop rate is reduced, and packets are sent with the least delay experienced.

Table 2. Scenario3: Delivery ratio

Application	**Max Delay (ms)**	**Proposed**	**MPLS**	**HetGrid**
Control1	500	95.4%	74.2%	**81.6%**
Control2	1000	96.2%	78.4%	**85.2%**
Control3	1500	97.1%	79.3%	**88.6%**
Monitoring1	4000	98.5%	83.2%	**89.8%**
Monitoring2	5000	99.7%	85.7%	**91.9%**
Monitoring3	6000	99.9%	88.4%	**93.5%**
Backup (log)	10000	100%	95.6%	**95.6%**

Figure 20 shows the latency experienced by QoS1 traffic in

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proposed method and HetGrid. As shown in this figure, in the proposed method, the delay time is less than the HetGrid method.

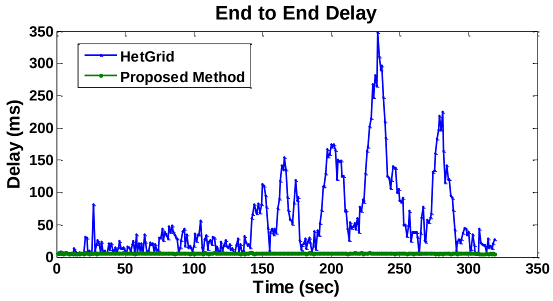

Fig. 20. Scenario3: delay (HetGrid vs proposed method)

D. Scenario Four: PDC timer evaluation

In this scenario, the effect of the PDC timer value on the packet drop rate is investigated. In the traditional methods the timer value is fixed, while in the proposed approach, the timer value is dynamically determined based on the network conditions. For this purpose, a network with 16 PDCs has been simulated. In the proposed model, the timer value is calculated iteratively for each PDC. This reduces the processing time of the PDCs and thus reduces network latency. As shown in Table 3, in the proposed model, less packets are dropped which indicates that determining the timer value can have a significant effect on reducing the latency and drop rate of packets.

Table 3. Scenario4: Packet drop rate

PDC	Timer Value	Percentage of deleted packets (Proposed Method)	Percentage of deleted packets(Fixed Timer)
1	0.017	0.01	0.10
2	0.049	0.03	0.05
3	0.048	0.01	0.17
4	0.045	0.04	0.21
5	0.031	0.01	0.16
6	0.028	0.02	0.07
7	0.04	0.02	0.23
8	0.027	0.02	0.17
9	0.053	0.01	0.10
10	0.051	0.04	0.13
11	0.047	0.01	0.19
12	0.019	0.02	0.30
13	0.045	0.03	0.21
14	0.04	0.03	0.18
15	0.047	0.03	0.22
16	0.043	0.04	0.29

V. Conclusion

In this paper, we presented a SDN-based infrastructure which can cover different application requirements of WAMS networks. The main objective of the proposed model is to improve the delay, jitter, bandwidth and fairness performance of the WAMS networks. Different traffic flows are categorized in different service classes. The network resources are allocated to the higher priority classes. We presented a QoS based algorithm which tries to find the optimal path that satisfy the QoS requirements. A content-aware active queue management method is also proposed which is based on the special specifications of the data in WAMS. As newer data has higher priority in WAMS applications, so, in the proposed queue management method, low priority packets are dropped sooner than the others. We have also proposed a method for dynamically setting the PDC timers based on the current network conditions. The timer value is optimized which reduces network end-to-end delay.

Simulation results confirm that the proposed model has significantly improves the WAMS networks performance. This provides higher reliability and increases fault-tolerance in WAMS which improves the total performance of the smart grid networks.

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