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PMU TRAFFIC EVALUATION IN WIDE AREA MONITORING AND CONTROL SYSTEMS

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Abstract: The paper offers a demonstration on the importance of applying complex Quality of Service mechanisms to guarantee reliable data delivery within the required end-to-end delay boundaries. All areas of the Smart Grid, from generation, to transmission and distribution and even consumption cannot function properly without reliable communication networks. Remote and timely information gathering about the behavior of the grid is one of the functions that impose the heaviest burden on the IP networks. The end-to-end delay is a very important issue in the field of real-time data delivery considering the critical nature of the energy sector. Simulation models are built to evaluate the traffic behavior and results are obtained from three different scenarios.

Keywords: *Smart Grid, PMU, communication protocols, end-to-end delay, OMNeT++.*

ТРАФИЧНА ОЦЕНКА НА УСТРОЙСТВА ЗА СИНХРОНИЗИРАНИ ВЕКТОРНИ ИЗМЕРВАНИЯ (PMU) В ШИРОКООБХВАТНИ СИСТЕМИ ЗА НАБЛЮДЕНИЕ И КОНТРОЛ (WAMC)

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Резюме: Статията представя приложения на комплексни механизми от качесвото на обслужване с цел гарантиране на надеждно предаване на данни в допустимите граници на закъсненията от тип „край-до-край“. Бъдещите интелигентни енергийни мрежи, включващи производство, пренос, разпределение и дори консумация на електроенергия ще функционират адекватно само при наличие на надеждни комуникационни мрежи. Нуждата от дистанционно и своевременно събиране на информация определя важността на IP мрежите, които ще се използват заедно с енергийните системи. Закъсненията от тип „край-до-край“ са много важен въпрос при предаването на данни в реално време, имайки в предвид естеството на енергийния сектор. В настоящата статия са разработени симулационни модели за оценка на трафика и са получени резултати при три различни сценария.

Ключови думи: *Smart Grid, PMU, комуникационни протоколи, закъснения край-до-край, OMNeT++.*

I. INTRODUCTION

One of the main advantages of the emerging Smart Grid (SG) – intelligent distribution and consumption is achieved mainly by the integration of information and communication technologies. All areas of the grid, from generation, to transmission and distribution cannot properly function without a reliable and secure communication system. The communication system relies on a variety of key techniques to meet the challenging requirements of its concept.

One of the topics that has been rapidly gaining interest is the Wide Area Monitoring and Control Systems (WAMC). It involves collecting critical data from a large region of the power grid through the use of synchronized phasor measurement units (PMU). The PMU can take synchronized measurements at rates of 30 to 120 samples per second [1]. This characteristic allows the PMU to be considered a part of the future Smart Grid real-time communication infrastructure. IP-based networks are the obvious choice for PMU communications as the gains obtained by using them is expected to significantly reduce cost, configuration complexity, and maximize the network reliability – important factors that are expected in the future grid. Despite the fact that IP networks are most suitable for Smart Grid communications, a large number of challenges has been introduced by the applications that are envisioned to achieve the required functionality in the SG concept. Most of these applications carry strict requirements for communication latency in the range of 20 milliseconds to 5 seconds, depending on the application [1, 3, 4]. The main application areas include real time monitoring and control, state estimation, real time congestion management, power system restoration and system integrity protection schemes [2].

The objective of this paper is to provide an up-to-date look on the particularities of real-time data delivery over wide areas. The discussed communication requirements are derived from the formulated power grid requirements, and based on them, a communication model for evaluation is proposed. To illustrate the behavior of PMU traffic, a best effort delivery test case is compared to an implementation of Quality of Service (QoS) and the results are presented.

II. REQUIREMENTS AND COMMUNICATION INFRASTRUCTURE

A. Requirements

The WAMC is a system in which PMU measurements are collected from a number of locations in the power grid. The measurements are sent to a control location where they are used for calculating results and making automated decisions. The communication infrastructure is the most important component of a WAMC system. Due to the PMU distribution over wide geographical areas and the ultra-low latency requirements, the communication network design represents one of the most challenging aspects of the Smart Grid development.

Recent studies show that PMU network traffic has moderate bandwidth requirements but a very low latency tolerance due to the requirement for real time data delivery. In [5], the authors estimated the generated data rate of a PMU with a single phasor sample to be 19.2 kbit/s (for a 40-byte communication message with 28-byte UDP+IP overhead) in case those samples are being taken 30 times a second. Keeping the same sample rate (30Hz) in [6], the bandwidth required to transport phasor data from 100 PMUs is 2.085 Mbit/s. Therefore, every single PMU will have a bandwidth requirement of 20.36 kbit/s for a single phasor sample.

An ultra-low latency requirement is defined in [4], stating that control applications require the one-way delivery time to be in the order of half or full power cycle over hundreds of kilometers. Considering the frequency of the AC current in Europe, f_{AC} = 50 Hz, the end-to-end latency should not exceed 20 ms. Fulfilling such requirements with the standard best-effort delivery in the IP networks is practically impossible – the TCP/IP protocol stack was never designed to work with such demanding applications that are crucial for the proper functioning of the power grid. Therefore, complex QoS mechanisms should be applied to guarantee reliable data delivery within the required latency boundaries.

B. Infrastructure

The communication requirements impose the development of the following topological data collection architecture (figure 1).

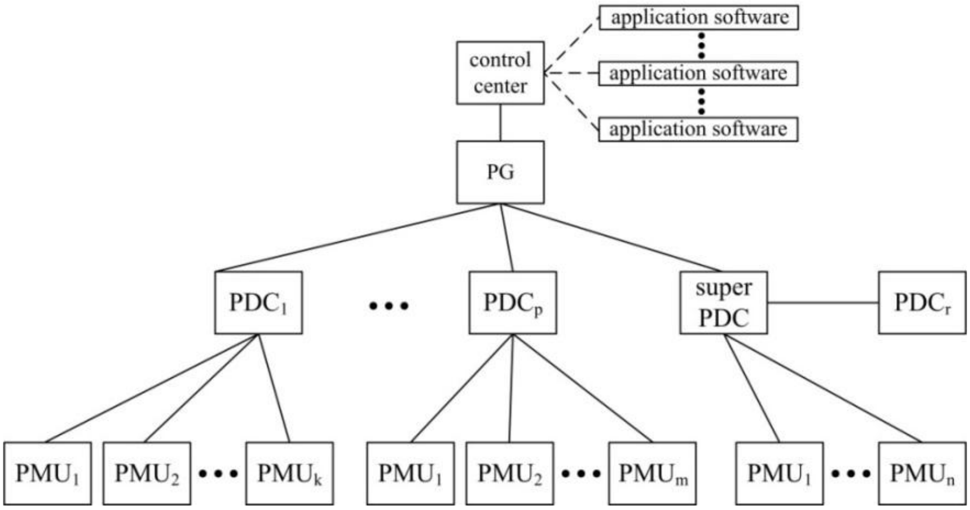

Fig.1. Data collection architecture

PMU: PMUs allow the measurement of synchrophasors (phasors that occur at the same time) directly from the grid. After analog-to-digital conversion (ADC), the phasor measurements are time stamped by a GPS clock. To encapsulate its data, the PMU is using the C37.118 communication protocol [7]. The created packets are then sent to a Phasor Data Concentrator (PDC) through the packet-switched wide area network.

PDC: A PDC is a network device that sorts and groups the received PMU data packets, based on their timestamps – packets with the same timestamp are encapsulated together. Depending on the network architecture and size, a Super PDC may be deployed to collect data both from PMUs and PDCs. The PDC also has other functionalities such as data archiving and error checking.

PG (Phasor Gateway): The PG accepts input data from multiple PDCs and, in some cases, from directly connected PMUs. The output date is designed for use by a control center’s applications and systems.

Control center*:* Monitoring and decision making functions are performed, control commands are formed and sent to controllable devices through the communication network. The decisions are made by software packages such as Energy Management Systems (EMS) and are based on the collected measurement data. Online state estimation, load forecasts, data archiving, economical dispatch and optimal power flow are some examples of EMS functions [8].

C. Data Format

According to C37.118 standard, a single PMU message is represented by the data formats shown on figures 2 and 3. Figure 2 illustrates the C37.118 message header and trailer, while figure 3 depicts the data frame.

First transmitted	SYNC (2B)	FRAMESIZE (2B)	IDCODE (2B)	SOC (4B)	FRACSEC (4B)

$DATA_1$	$DATA_2$	• • •	$DATA_n$	CHK (2B)	Last transmitted

Fig.2. C37.118 header and trailer

STAT (2B)	PHASORS (4/8B)	FREQ (2/4B)	DFREQ (2/4B)	ANALOG (2/4B)	DIGITAL (2B)

Fig.3. Measurement data fields

The size of the C37.118 header and trailer is fixed at 16 bytes. Depending on different PMU configurations and scenarios, the number of data frames and the size of each data frame will vary. For example, with a single measurement channel, the complete message size will vary between 30 bytes and 40 bytes. After encapsulation into the lower layers - the transport, network and link layers cause additional overhead to the communication message.

III. MODELLING AND CASE STUDIES

In this section the simulation models, built to evaluate the traffic behavior of PMUs, are described. The models are built within the OMNeT++ simulation environment [9] using the INET framework [10]. While the models do not represent an actual deployed network, they are aimed to provide characterization for future implementation of real-time data delivery in the power grid.

A. Network model

The initial network graph, figure 4, contains 47 nodes and 58 communication links. The nodes are categorized into four different types:

- *PMUs* – 16 units are deployed in 7 different access networks. Each of them represents one distribution substation local area network (LAN). For simplicity, we are assuming every PMU has 16 measurement channels, resulting in 384 bytes generated raw data per sampling period. Considering f_{AC} = 50 Hz, the sampling rate is chosen to be one sample per power cycle which results in 20ms long sampling period.
- *Background traffic generators* – two types of competing IP traffic are implemented in the model – video surveillance and voice over IP (VoIP) calls between the different substations and the control center. The video traffic is modelled as MPEG-4 compression, 24 frames per second with constant bitrate (CBR) generation over the UDP protocol. VoIP calls are assumed to be G.711a with throughput of 64 kbit/s per call (88 kbit/s with overhead) over the RTP protocol for voice samples and SIP for signaling.
- *Access routers* – substation gateways connecting the LANs to the core network which are also serving as PDCs. The LAN interfaces are configured as 802.3 Fast Ethernet while the WAN interfaces are using the Point-To-Point Protocol (PPP).
- *Core routers* – the core network is the backbone connecting all the substation LANs and the control center LAN. The routing is modelled as OSPFv2 routing protocol

which is based on the Dijkstra’s shortest path algorithm [11]. The core network’s area ID has been set to 0.0.0.0, while the substation and control center networks have area IDs 0.0.0.1 to 0.0.0.8.

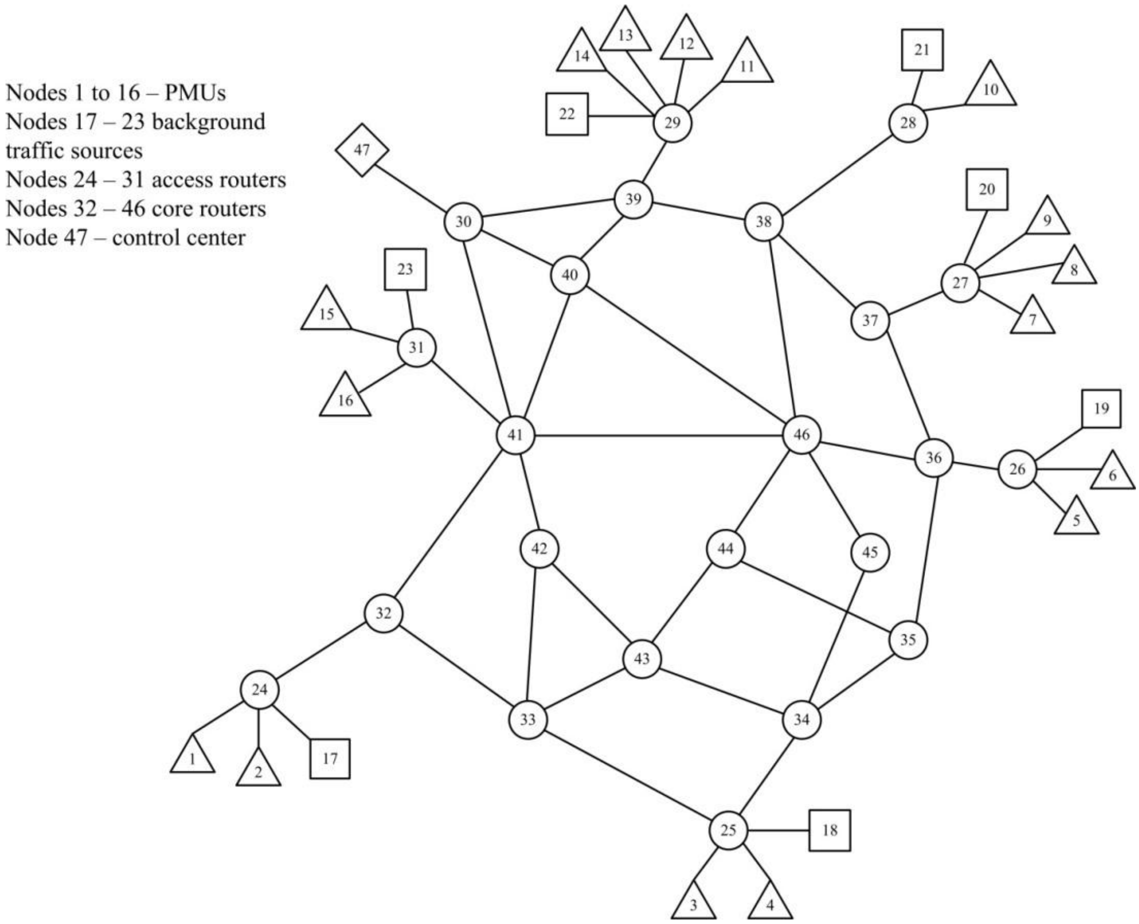

Fig.4. Network topology

The addressing is IPv4 with core routers IP addresses set in the 10.0.0.0/24 address pool and the substation and control center network interfaces set from 192.168.1.0/24 to 192.168.20.0/24. For all the network scenarios the maximum transmission unit (MTU) size has been set to 1492 bytes at the network layer. It differs from the usual 1500-byte MTU due to the use of PPP and PPPoE, adding 8 bytes to the total overhead. Because of the inability of C.37.118 devices to process fragmented packets, fragmentation is not considered in the current model. A summary of the protocols and traffic characteristics used in all scenarios is shown in table 1 and table 2.

TCP/IP layer	Protocol	Overhead
Application	C37.118	16 bytes
Transport	UDP	8 bytes
Network	IPv4	20 bytes
Link	PPP PPPoE 802.3 Ethernet	2 bytes 6 bytes 18 bytes

Table 1. Used protocols for the PMU traffic and their overhead

Type of traffic	Generation rate (packets/s)	Packet size in bytes (both payload and overhead)	Required bandwidth per unit
PMU	50	454	181.6 kbit/s
Video surveillance	100	1251	1.22 Mbit/s
VoIP	50	220	88 kbit/s

Table 2. Comparison of the traffic generation characteristics for the three types of traffic

B. Scenario case studies

In order to evaluate the PMU traffic behavior, three different scenarios were developed:
Best effort delivery – in this scenario no QoS schemes are present and the “lightweight” UDP protocol was chosen to carry the PMU data at the transport layer. In comparison to the slower and reliable TCP, UDP has no packet delivery assurance but offers lower protocol-related delays and smaller overhead. TCP is unsuitable for transmission of data with delay sensitivity of such magnitude due to its “three-way handshake” and “TCP slow start” mechanisms.

The interface queues in this scenario are simple drop tail queues with frame capacity of 100 and the bandwidth of the core network links is selected to be 2, 4 and 6 Mbit/s per simulation run.

QoS implementation - diffserv Expedited Forwarding (EF) with 40% bandwidth reserved for PMU traffic. All the core routers are configured to prioritize PMU packets over the background traffic to ensure lower end-to-end delay than the best effort scenario. To enable comparison of the traffic behavior between the different scenarios, the core links bandwidth is kept the same. The packet schedulers are modeled to use random early detection (RED) queueing discipline to address the issue of the core network becoming under-utilized and congested by turns. The queueing buffer capacity is increased to 5000 frames to avoid high packet drop rates.

Link failures – to evaluate the end-to-end latency behavior during critical network conditions, an xml script was developed to conduct changes to the second scenario during its simulation runs. Four random core links are being disconnected at simulation times t_s = 40s, 55s, 80sand 90s. At t_s = 160s the first three links return to connected state, followed by the fourth at t_s = 180s.

IV. SIMULATION RESULTS

The most important parameter that was collected during the simulations is the end-to-end (ETE) delay. ETE delay is measured by calculating the time needed for a certain packet to travel from the network source to the network destination. It is calculated using equation (1):

$$\mathrm{ETE_D} = \sum_{i=1}^{n} \mathrm{D_Q} + \sum_{i=1}^{l} \mathrm{D_P} + \sum_{i=1}^{l} \frac{\mathrm{L_P}}{\mathrm{R_i}} + \sum_{i=1}^{l} \frac{\mathrm{d_i}}{\mathrm{s}} \qquad (1)$$

where n is the number of intermediate nodes between source and destination, l is the number of network links between source and destination and $l = n+1$, D_Q is the queueing delay at each node, D_P is the processing delay which is often neglectable and is set to 100 μs in the current study. L_P / R represents the transmission delay for each link where L_P is the packet length (in bits) and R is the capacity of the link (in Mbit/s). Propagation delay of a link is calculated as $D_{prop} = d / s$, where d is the link length and s is the propagation speed of the medium. Assuming fiber optic transmission medium is used, the propagation speed is 3 x 10^8 m/s.

Figure 5 depicts the average ETE delay in the best effort scenario for the three core link bandwidth cases. All the C37.118 packets experience delays higher than the desired value of 20 ms. Even with the 6 Mbit/s links, the lowest ETE delay value is 37 ms. The fluctuations at the start of the simulation runs are due to initialization of the OSPFv2 routing, dynamic addressing and ARP tables population. The simulation results for the background traffic delays are shown on figure 6. Considering the maximum acceptable ETE delay values for video and voice transmission over IP - 150 ms, the results show requirement fulfillment only in the case with 6 Mbit/s core links.

The results from the QoS scenario (fig.7, fig.8) show drastically reduced values for PMU traffic ETE delays even in the worst case with 2 Mbit/s – after the network goes into a steady state, all the cases cover the required upper bound of 20 ms. For the background traffic, the 2 Mbit/s case show unacceptably high delay values with a maximum of 576 ms for the voice traffic and 332 ms for the video traffic. The other two cases fit in the required values, with less than 100 ms delay during the steady network operation.

The results obtained from scenario set 3 with 2 Mbit/s links are presented on figure 9 and figure 10. The case without any QoS support show similar behavior for the three types of traffic without any cover of the requirements. With traffic prioritization, the ETE delay is kept on the requirement upper bound with a maximum of 20.6 ms during the steady network operation. Even with 4 random links being disconnected during the simulation runs, the low ETE delay and packet loss provided by the QoS support are evident in the latter results. The packet loss and maximum queueing time parameters are summarized for the three scenarios in table 3.

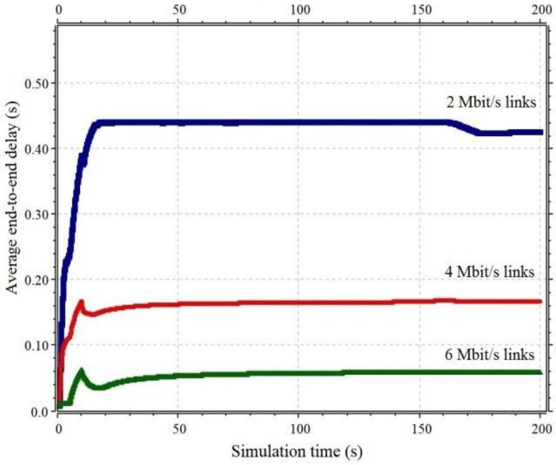

Fig.5. Scenario 1 ETE delay for PMU traffic

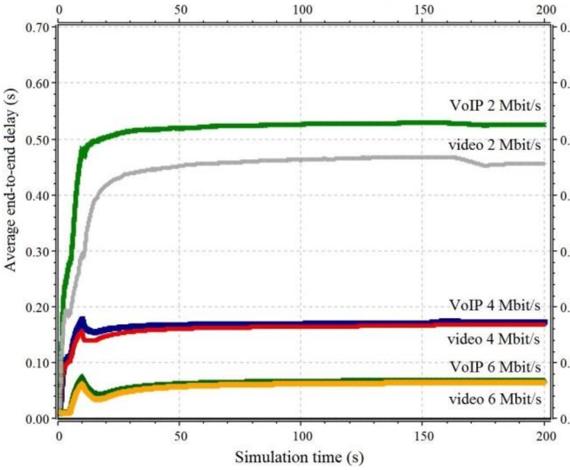

Fig.6. Scenario 1 ETE delay for background traffic

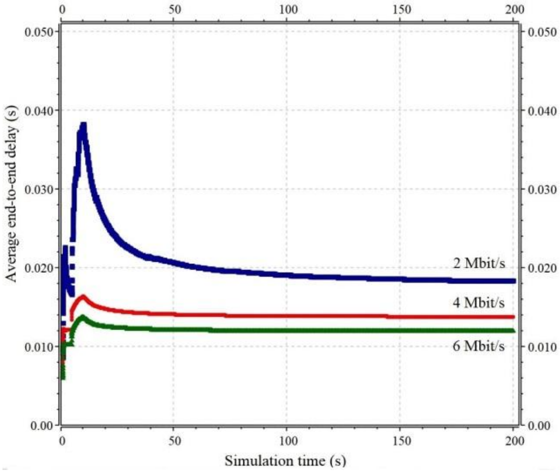

Fig.7. Scenario 2 ETE delay for PMU traffic

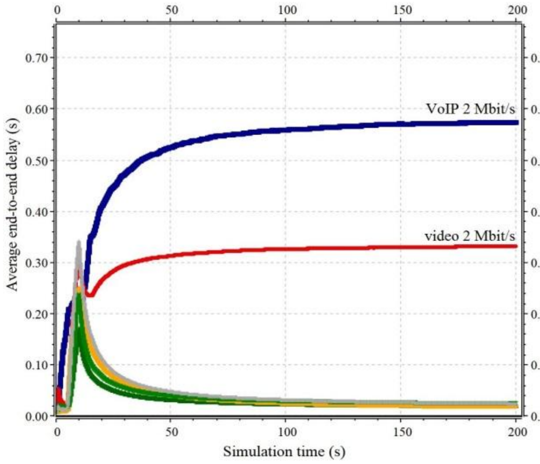

Fig.8. Scenario 2 ETE delay for background traffic

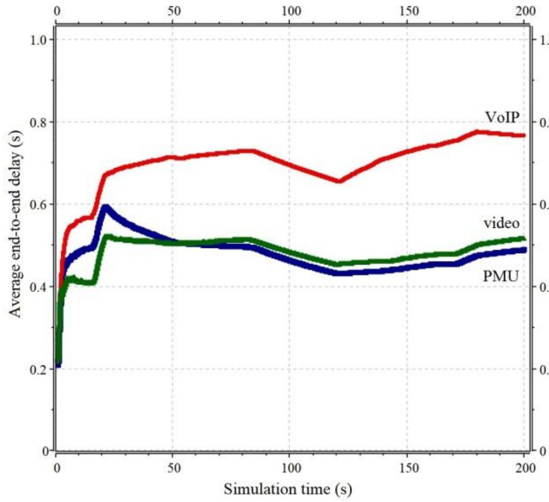

Fig.9. Scenario 3 ETE delay with no QoS

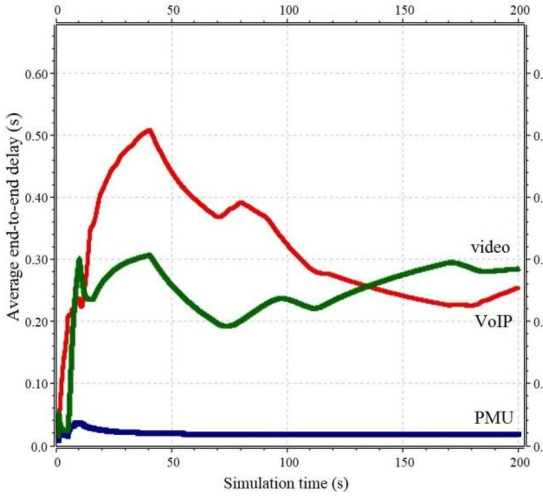

Fig.10. Scenario 3 ETE delay with QoS

		Link bandwidth	**Packet loss (%)**	**Maximum queueing time (ms)**
scenario 1: best-effort case		**2 Mbit/s**	67.01	405
		4 Mbit/s	31.69	208
		6 Mbit/s	3.19	143
scenario 2: QoS case		**2 Mbit/s**	0.81	544
		4 Mbit/s	0.46	25
		6 Mbit/s	0.036	14
scenario 3: link failures case	**no QoS**	**2 Mbit/s**	75.23	785
	QoS	**2 Mbit/s**	1.58	529

Table 3. Summary of simulation results

V. CONCLUSION

One of the most important aspects of the future intelligent power grids will be WAMC applications, enabled by the rapid development of PMUs that can offer real-time monitoring.

The proper selection of network protocols, topologies and transmission medium will play crucial role in fulfilling the envisioned WAMC concept. However, such selection is difficult to be developed without the exact knowledge of the requirements for network delay, bandwidth, QoS, etc.

In the current paper, the ETE delay is investigated in the WAMC context and its impact on the system is outlined. The developed network models were used to demonstrate the absolute requirement for advanced network approach in terms of using complex QoS mechanisms in order to guarantee reliable and timely data delivery.

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