Communication Network for Remote Monitoring of Wind Turbine Based on Infrared Camera

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***Abstract*—Recently, numerous monitoring techniques have been proposed to detect the failure of wind turbine (WT). These techniques were developed based on embedded system with several sensors and complex cabling requirements. Therefore, an Infrared (IR)-camera can be considered an effective visual tool with a large coverage area, high accuracy, reliability, and cost effectiveness. This paper proposes communication network architecture for remote monitoring of WT based on non-contact IR-cameras to detect the failures in real-time. Firstly, the feasibility study of various components such as electrical, mechanical and control system of WT which can be monitored through IR-camera was conducted. According to the feasibility study, the WT components are then prioritized into three different categories of high, low, and medium. According to the aforementioned categorization of WT components, three different types of IR-camera with a low, medium, and high resolution are used. The communication network is designed in two parts the internal communication network inside the WT and the external communication network between WT and remote control center. The amount of data traffic is numerically modeled with different parameters such as image resolutions, frame size, frame number, and data rates for the transmission of data. Since, the external communication network is usually shared by other sub-networks for different applications. This can lead the problem of high bandwidth demand and security issues. Therefore, different compression techniques such as MPEG-2 and H.264 are considered to evaluate the network performance. The communication network is modeled and simulated through OPNET. The simulation results show that the end-to-end delay of the IR-camera based monitoring can satisfy the IEEE 1646 standard timing requirements.**

I. INTRODUCTION

Renewable energy plays a significant role to fulfill the growing energy demand of industries and other utilities. Therefore, the wind power industry has been increased dramatically over the past few years. However, the rapid growth of wind power pushed the power plants into mountainous and offshore areas. Due to these remote areas, the wind power industry faces various challenges such as fire and failure of components [1]. The failure of turbine component has a direct impact on the WT availability. To meet new challenges the WT should be operational and available all the time, without any breakdown. The expensive operation and maintenance cost of WT (especially in offshore) has attracted the researcher's attention towards the reliability and maintenance issues. The condition monitoring system (CMS) is considered as a preemptive strategy that employs monitoring technique at every critical location of the WT. Currently, several CMS techniques are in used. These techniques are vibration analysis, acoustic emission, ultrasonic testing, oil analysis and strain measurement which are based on sensor nodes utilized in the system [2]. The communication network can prevent the WT breakdown through monitoring which can increase the operational life with fewer failures. Several communication architectures have been proposed in the literature, such as hybrid communication network architectures for monitoring large-scale WT using video surveillance system as part of the WT monitoring and control system. The study considered CCTV with image resolution of 128 * 240 pixels, color depth of 9 bit/pixel and 15 frames/sec [3]. In our previous studies, we proposed and simulate sensor based and IR-based communication network architecture for WT/WPFs monitoring and control system [4], [5], [6], [7], [8]. For structural health monitoring of different components and equipment, temperature is used as common indicators. Recently, the infrared thermography (IRT) has become a matured technology that is used as part of condition monitoring tools to measure the temperature in a non-contact and in real time. IRT is now considered the most effective visual tools for more accurate, reliable, and cost effective technique because of the advent of newer IR-camera generation. The infrared thermography technique is proposed as an integrated condition monitoring system to be used with the existing monitoring system as a retrofit design to increase the performance of an early fault detection system [9]. With the use of non-contact and large area coverage IR-camera, the IRT based monitoring technique can reduce the instrumentation [10]. Fig. 1 shows a schematic diagram of WT monitoring with IR-camera. Different components of WT, such as electrical and mechanical are equipped with an IR-camera to continuously inspect their condition.

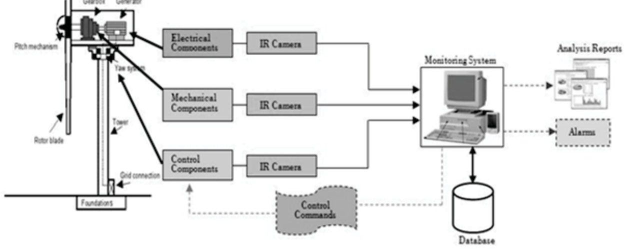

Fig. 1. Schematic diagram of IR-camera based wind turbine monitoring

The monitoring and control system uses different techniques to analyze the results of the monitoring components and generates reports, alarms, and control commands. This paper models the communication network architecture for monitoring and control of WT in real-time. A sensor based, monitoring is considered for meteorological mast while IR-camera based monitoring is used for the other components. We study the feasibility of different WT's components such as electrical, mechanical and control system for IR monitoring. The amount of data traffic is numerically modeled with different parameters for IR images such as color depth sensors resolutions, frame size, frame number, and data rates. We design internal and external communication network. The simulation results are validated with the amount of data received at the wind turbine controller (WTC) and control center. The performance of communication network is analyzed in view of end-to-end delay, which can satisfy the IEEE 1646 standard timing requirements.

The rest of this paper is structured as follows. Section II defines the IR technologies, provides the feasibility study of different WT components to be monitored with IR technology and then prioritize these components. Section III design the internal and external communication network architecture and represents numerical calculation of data traffic for meteorological mast and IR-camera with/without different compression techniques. The simulation setup and results are discussed in section IV. Finally, Section V summarizes the paper with conclusion and future direction.

II. Infrared technologies for wind turbine monitoring

A. *The role of infrared thermography in wind turbine monitoring*

Infrared thermography (IRT) is based on Infrared techniques that work by the temperature profiling of an object surface. The mechanism is as every object emits IR radiation, which is the function of temperature. In the electromagnetic spectrum, the IR has a higher spectrum range of 0.8 to 1000-micron wavelength. The IR system can scan, detect, and measured IR energy from the surface of the target object [11]. An infrared camera is a non-contact device that creates images using infrared radiation unlike to common camera which form the image through visible light. The IR-camera operates with longer wavelength of 14,000 nm (14 μm) and lower frequencies than regular visible light. It works regardless of the lighting conditions and can capture the data in areas even in the absence of any light. IRT can play a significant role in the monitoring of WT components. The feasibility study of IR-camera based monitoring for WT components can be done through the type of fault associated with WT components. In the WT operating condition, the electrical components can spark due to vibration and causes overheating. With IRT, it can be possible to inspect the faulty cable and get an immediate image of the potential problem. Fire is one of the major problems in WT to deal with because the wind power plant located in rural areas, long distances, and have long 100-meter-high tower. Smoke and flame detectors are used to detect the fire. However, there is a limited probability to extinguish the fire in a WT due to punitive environmental condition. With IRT the fire detection can be made at an early stage by positioning the IR system to the components that causes overheating. Similarly, the mechanical brake can cause increases in temperature and mostly the problematic mechanical devices should be replaced which can increase system downtime. But with the use of IR monitoring it can be possible to provide early detection to save resources replacements and make the downtime limited [12].

B. *Wind turbine components for monitoring with infrared camera*

The WT components can be categorized into monitoring components and control components. The category of monitoring, defines the components to be monitored for fault. The category of control, includes those components which could be used to control the WT operation. The first category components for IR-camera monitoring are prioritized based on the problems associated with these components. For example, the WT components, including electrical system (power electronics, control system), high voltage transformer, nacelle, and turbine are more feasible for the IR thermography. These components are at high risk for short-circuit, fault and fire which can raise their temperature and hence are of high priority for IR-monitoring. Similarly, the other components are categorized as medium and low priority. According to reference [12], based on the problem associated with WT's components and IR monitoring requirements, the Table I provides a detailed description for the low, medium, and high priority components of a WT for monitoring with IR thermography.

TABLE I. . Feasibility and prioritization of WT's components for monitoring with infrared [12]

WT Subsystem	Components	Problems	Requirements	Priority
Drive Train	Main shift bearing	Wearing	Continuous	Low
	Mechanical brake	Locking Position		Medium
	Gear box	Wearing, fatigue, oil leakage, insufficient lubrication		Medium
Auxiliary System	Yaw System	Yaw motor brake locked, gear problem	Continuous	Low
	Pitch System	Pitch motor problems		Medium
	Hydraulic System	Pump motor problems, oil leakage		Medium
	Sensors	Broken		Medium
Electrical System	High Voltage	Contamination, arcs	Continuous and at Service	High
	Power Electronics	Short circuit, component fault, bad connection		High
	Control System	Short circuit, component fault, bad connection		Low
Tower	Nacelle and Turbine	Fire	Continuous	High
System Transformer	-	Problems with contamination, Breakers, Disconnectors, Isolators	Continuous and at Service	High

A meteorological tower equipped with different instrumentation is used to collect the wind data and other information such as temperature, humidity, and pressure, etc. Typically, the towers are 70 m tall and configured with instrumentation (sensors) at 50 m and 70 m [13]. The meteorological information such as wind speed, temperature, humidity can be used to control the WT accordingly. These information's should be monitored with different sensors rather than an IR-camera. In this paper, we considered meteorological information from IEC 61400-25 standard. The description of these different sensors located within the meteorological tower is shown in Table II.

TABLE II. METEOROLOGICAL MAST PARAMETERS BASED ON IEC 61400-25-2 STANDARD

Sensor Name	Description
MetAlt1HorWdSpd	Horizontal wind speed
MetAlt1VerWdSpd	Vertical wind speed
MetAlt1HorWdDir	Horizontal wind direction
MetAlt1VerWdDir	Vertical wind direction
MetAlt1Tmp	Temperature
MetAlt1Hum	Humidity
MetAlt1Pres	Pressure

III. COMMUNICATION NETWORK ARCHITECTURE FOR MONITORING OF WIND TURBINE BASED ON IR-CAMERA

IR-technology can add important predictive information for several components in WT. The communication network consists of two sub-networks called the internal communication network and external communication network. The following section describes the function, main components, and communication channel in each sub-communication network. Then we calculate the data traffic for IR-camera based monitoring with and without considering different video compression techniques.

A. Internal communication network

The internal communication network is used inside the WT. This sub-network is based on [14]. The main components connected by this network include IR-cameras, CMS and wind turbine controller (WTC). The monitoring data are collected at the data collection unit through the internal communication network interface.

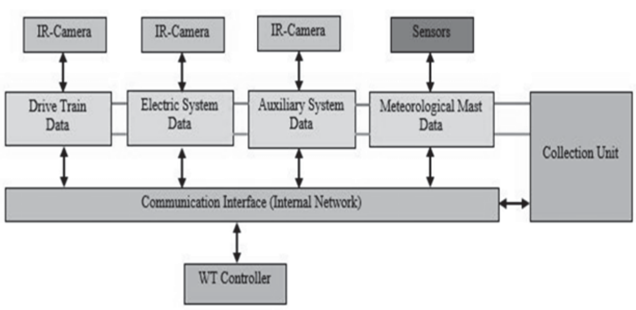

Fig. 2. Internal communication network architecture within WT

Several communication technologies such as Ethernet, fiber optic, Wi-Fi and/or ZigBee can be used for communication amongst the IR-cameras, sensors, data collection unit and WT controller Several IR-cameras located at WTs continuously monitors different WT's components such as Electrical, Mechanical and Control system. A meteorological tower (also called meteorological mast) within WT uses sensors to collect the wind profile. All the monitoring information collected at the data collection unit is transmitted to the WTC for necessary action and onward transmission to the control center. The main components of the CMS are sensors, IR-cameras, and data collection unit. This paper considered wired Ethernet communication channel to connect the CMS with WTC located at the bottom of the tower. The internal communication network architecture is explored in Fig. 2, with a detail of data collection from IR-Cameras and sensors at the data collection unit and WTC.

B. External communication network

The external communication network enables the remote control center (CC) to monitor the WTs. Fig. 3 shows the proposed network communication architecture for monitoring different components of WT using an IR-camera. It connects the CC to the WTs through the WTC. The WTC is an autonomous system located at the bottom of the turbine, which can enable the WTs to be controlled locally and by the remote control center. The WTC serves as an interface between the CC and WTs monitoring and control devices. The main components of WTC include the processing unit which processes the IR-camera and Meteorological mast information. The Met. Mast information is used for wind profile to send commands to the actuator through a programmable logic controller (PLC). In view of [15] various functions such as turbine state transition control, control of auxiliary system and visualization and human machine interface (HMI) are performed by the WTC are discussed. In real system the WTs are connected to the grid for collection and distribution. The external communication link of the WTC with the remote control center may be shared by other application and sub-networks in the grid. This can lead to the problem of high bandwidth demand and security issues. Thus the WTC process the IR-camera information and applied different compression techniques to avoid the aforementioned problem in external communication with the control center. Two kinds of image analysis techniques discussed in [16] can be applied to inspect the different components of WTs. These techniques are quantitative and qualitative. According to the above reference the quantitative technique takes the exact temperature values of the target objects. The environmental factors such as temperature and humidity can affect the accuracy of the analysis. This technique is generally used to identify the abnormal condition of components with high temperature. The qualitative technique uses a relative different method such as surface reference temperature of target and other relevant surface to get the abnormality in the temperature. The control message will be generated according to these conditions. However, the complete details of how the analysis algorithm are working and how these values of surface temperature, variation in temperature and temperature difference ratio are obtained is beyond the scope of this work and the readers are referred to reference [16].

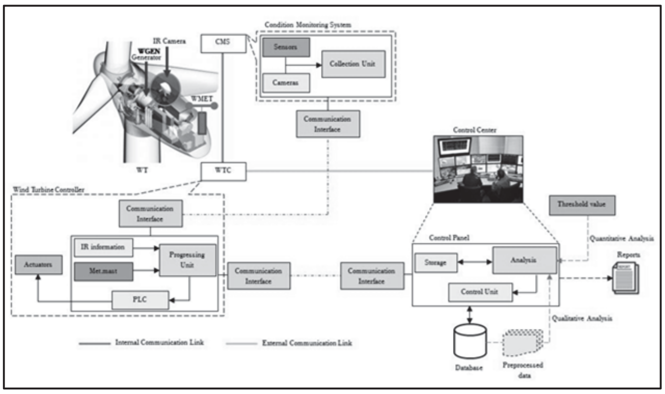

Fig. 3. Communication network architecture for IR-camera based WT monitoring and control system

C. *Traffic modeling for meteorological mast*

The calculation of meteorological data is based on the measurement devices, sampling frequency, number of channel and data rate for each channel [17]. Table III shows the measurements, sampling frequency, and data rate for each measurement according to equation (1).

$$D_R = 2(M_C * F_C) \quad (1)$$

Where, D_R : Data rate, M_C : number of channel and F_C : sampling frequency, 2 bytes is the size of data for each measurement device.

TABLE III. DATA TRAFFIC FOR METEOROLOGICAL MAST

Measurements	Sampling Freq.	Data(byte/s)
Temperature	1Hz	2
Pressure	100Hz	200
Humidity	1Hz	2
Horizontal wind direction	3Hz	6
Vertical wind direction	3Hz	6
Horizontal wind speed	3Hz	6
Total		228

D. *Traffic modeling for IR-camera*

1) Without compression techniques: The thermal camera creates images from the heat radiated by the target object. The camera works fine regardless of the unfriendly surroundings light conditions, such as shadows, backlight, darkness, and even masked objects. The camera images are then delivered to the CC to allow operators to detect and act on suspicion. IRT can hence be a suitable technique for WTs monitoring. The data rate for IR-camera can be calculated as follows from equation (2) and (3).

$$F_S = R_Z * D_S \quad (2)$$

$$D_R = F_S * FPS * N_C \quad (3)$$

Where
F_S: Frame size, R_Z: Resolution, D_S: Detection sensors (color depth), FPS: Frame per second and N_C: Number of camera.

This paper considered three types of IR-cameras with low (160*128), medium (320*240), and high (384*288) resolutions. The consideration of these resolutions is based on Table I. The detection sensors are of 9 bits/pixel and frame rate of 30 FPS. By using equation (2) and (3) Table IV summarizes the frame size (byte) and data rate (Mbps) for the camera resolution without considering any compression techniques.

TABLE IV. DATA FOR IR-CAMERA BASED MONITORING WITHOUT COMPRESSION TECHNIQUES

Resolution (Pixels)	No of Camera	FPS	Frame Size (byte)	Data Rate (Mbps)
Low	3	30	184320	118.65
Medium	5		691200	791.01
High	4		995328	911.25

2) With compression techniques: A major challenge for transmission of digital video is an uncompressed raw form that requires huge amount of data to be transmitted. The goal of video compression is to represent the video stream using few possible bits with maintaining the quality through compression algorithms. The compression algorithms retain the minimum required content while removing less relevant redundant information. The elimination of unnecessary contents from the information allows a more efficient storage and transmission of the video streaming. Two primary standards organization driving the definition of image and video compression. The International Telecommunications Union (ITU) defined H.26X standard series with focus on telecommunication applications. International Standards Organization (ISO) defines JPEG standards for still image while MPEG standards for moving images [18]. The Motion Imagery Stands Board (MISB) ST 0404-01 recommends MPEG-2 compression with lower bits for the compatibility with legacy system [19]. While the H.264 standard is the preferred compression for new system with high quality [20]. This paper considered MPEG-2 and H.264 compression with 9 bits/pixel detection sensors for monitoring of WTs in real-time. The following equation (4) can be used to express the video frame compression ratio, while applying the compression ratio, equation (5) defines the percentage reduction in frame size. Equation (6) and (7) can be used to define the compression ratio in the video stream, and percentage reduction in the data rate of the video stream.

$$C_{FR} = \frac{U_{FS}}{C_{FS}} \quad (4)$$

$$P_R = 100 * (1 - \frac{C_{FS}}{U_{FS}}) \quad (5)$$

$$C_{DR} = \frac{U_{DR}}{C_{DR}} \quad (6)$$

$$P_{DR} = 100 * (1 - \frac{C_{DR}}{U_{DR}}) \quad (7)$$

Where:

C_{FR}: Compression ratio in frame size, U_{FS} : Uncompressed frame size, C_{FS} : Compressed frame size, P_R : Percentage reduction in frame size, C_{DR}: Compression ratio in data rate, U_{DR} : Uncompressed data rate, C_{DR}: Compressed data rate and P_{DR}: Percentage reduction in data rate.

Table V considers different compression ratio for image and video streaming using MPEG-2 and H.264 compression standard techniques [21]. Using equation (4) and (5) Table VI summarizes the compression in frame size by applying MPEG-2 and H.264 techniques, according to Table V and considering 9-bit detection sensors/pixels. Using equation (6) and (7) and the compressed frame size from Table VI, Table VII shows the compression in data rate.

TABLE V. DATA RATE FOR IR-CAMERA BASED MONITORING WITH COMPRESSION TECHNIQUES

Media Type	Compression Technique	Compression Ratio
Image	JPEG	10:1
Video	MPEG-2	30:1
	H.264	60:1

TABLE VI. COMPRESSION IN FRAME SIZE THROUGH MPEG-2 AND H.264 STANDARDS COMPRESSION TECHNIQUES

Resolution Type	Frame Size(byte)	Compressed Frame Size(byte)	
		MPEG-2	H.264
Low	184320	6144	3072
Medium	691200	23040	11520
High	995328	33178	16589

TABLE VII. COMPRESSION IN DATA RATE THROUGH MPEG-2 AND H.264 STANDARDS COMPRESSION TECHNIQUES

Resolution Type	Number of Camera	FPS	Compressed Data Rate(Mbps)	
			MPEG-2	H.264
Low	3	30	4.23	2.11
Medium	5		26.37	13.18
High	4		30.37	15.19

E. Communication timing requirements:

There is no specific timing requirement defined by the IEC 61400-25 standard for WTs/wind power plant communication network. Therefore, in this paper the IEEE 1646 standard communication delivery time performance requirements for electric power substation automation described in the above Table VIII is considered [22].

TABLE VIII. . IEEE 1646 STANDARD COMMUNICATION DELIVERY TIME, PERFORMANCE TIME REQUIREMENTS FOR ELECTRIC POWER SUBSTATION AUTOMATION

Information Type	Internal to Substation	External to Substation
Monitoring and Control Information	16 ms	1 sec
Operation and Maintenance	1 sec	10 sec
Image File	10 sec	60 sec
Audio and Videos Data Stream	1 sec	1sec

IV. SIMULATION RESULTS AND DISCUSSION

A. Communication Network Scenario in OPNET

Fig. 4 shows the network model of communication network architecture for WTs monitoring and control system based on IR-camera. The network is modeled through OPNET [23]. The model consists of internal and external communication network. The internal communication network connects the meteorological mast and IR-cameras to the WTC. External communication network is used to communicate between WTC and control center server. We considered three different resolutions with 30 FPS and simulate several scenarios for one WT using LAN. The OPNET model consists of one Meteorological mast and 12 IR-cameras: 3 for low resolution, 5 for medium resolution, and 4 for high resolutions. The IR-cameras are connected to the Ethernet switch which transmits video imagery to the control center via the WTC system. The control center process the video at server for appropriate action. Each of the Ethernet workstations is represented by one IR-camera. We considered Ethernet channels of 1Gbps for internal and 100Mbps for external communication. We configure wind turbine video conference application and profile to support the outgoing stream of video frames.

B. Results for meteorological mast

In this section we discuss the results of internal and external sub-communication network for meteorological mast data. Fig. 5 shows that 228 bytes is the amount of data received at the WTC and CC which follows the traffic calculation in Table V. The end-to-end delay for both internal and external communication networks is 0.13 ms and 0.22 ms respectively. These latencies are depicted in Fig. 6. The cause of a higher delay in the external communication network is the lower channel capacity of 100Mbps.

C. Results based on IR-camera monitoring

1) Without considering Compression Techniques: To verify the simulation results the amount of data traffic received at video server in the control center is compared with our numerical analysis for uncompressed video streaming. To support high data streaming traffic, this scenario considered a 1 Gbps Ethernet communication link for the internal sub-network. Fig. 7 shows the data received without compression for low, medium, and high resolutions of IR-camera with 30 FPS. The amount of data received at the WTC is 118.65 Mbps (Low), 791.01(Medium) and 911.25 (High) which validate our numerical analysis summarized in Table VI.

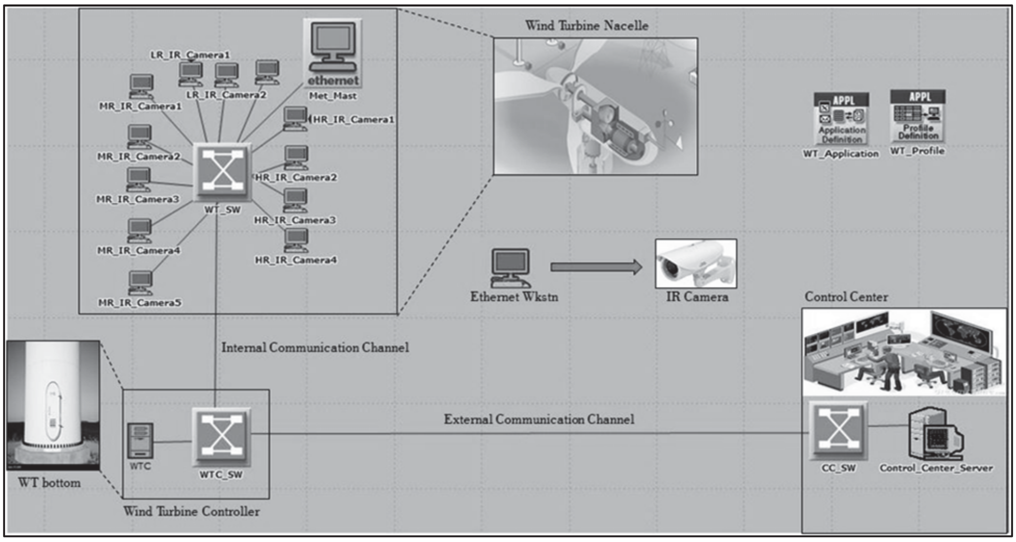

Fig. 4. OPNET based communication network model for monitoring WT using IR-camera

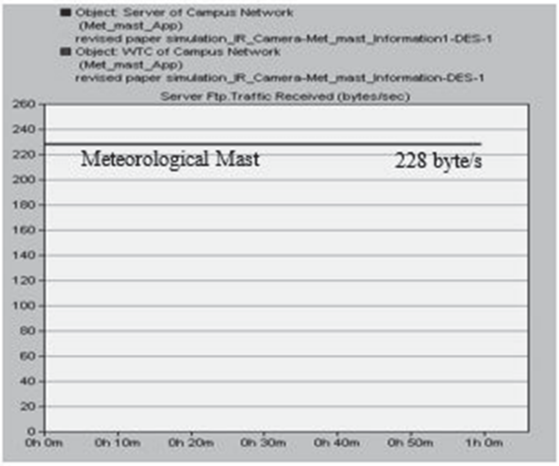

Fig. 5. Amount of received data for met. mast

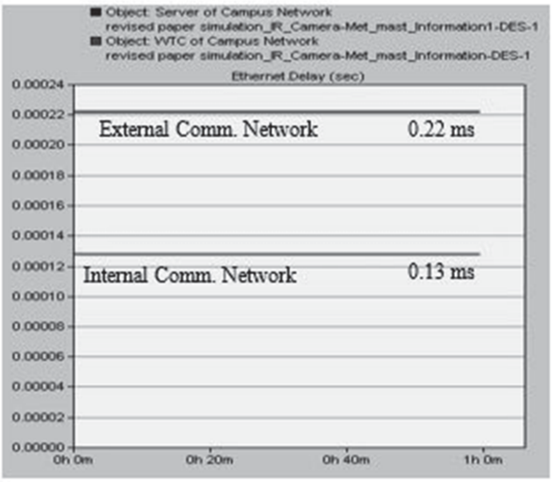

Fig. 6. End-to-end delay of met. mast data

Fig. 8 shows the end-to-end delay without compression for low, medium, and high resolution with 1Gbps link capacity. The end-to-end delay is 2.35 ms, 14.54 ms and 16.73 ms respectively.

2) Results with compression: This section discusses the simulation results in view of data received at the video server in the CC servers and the latency by considering the compression MPEG-2 and H.264. According to Table VII and Table VIII, there is a significant reduction in frame size and hence in the data rate which is 96.67% and 98.33% for MPEG-2 H.264 respectively. To utilize the link capacity in our consequent scenarios we considered a 100Mbps Ethernet communication channel as a main external communication link between the CC and WT. The simulation results in Fig. 9 and Fig. 10 shows the data received with MPEG-2 and H.264 compression, which follows our numerical calculation in Table IX. The network latency with MPEG-2 and H.264 is shown in Fig. 11 and Fig.12. The end-to-end delay with MPEG-2 for high, medium, and low resolutions is 5.91 ms, 4.82 ms and 1.15 ms respectively. However, with H.264 the network latency is almost half as compared to MPEG-2. The end-to-end delay with H.264 is 3.22 ms, 4.77 ms and 0.75 ms respectively. The simulation results without and with compression of MPEG-2 and H.264 clearly indicate that the simulation model follows IEEE 1646 standard timing requirements of electric power system.

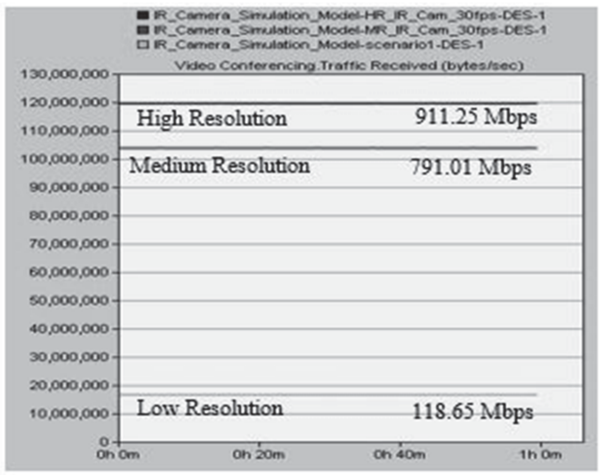

Fig. 7. Amount of data received for low, medium and high resolution IR-camera

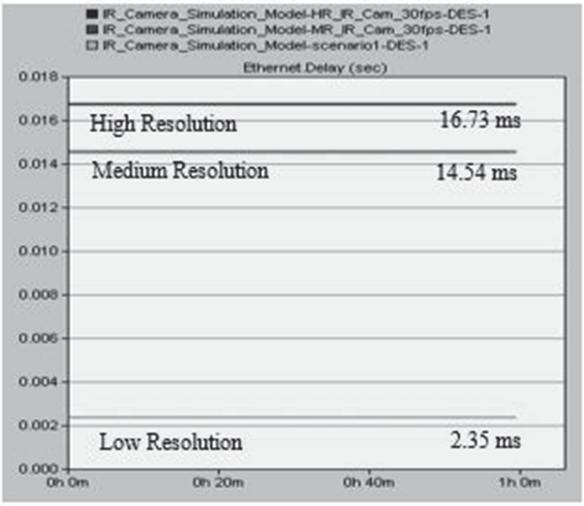

Fig. 8. End-to-end delay of low, medium and high resolution IR-camera

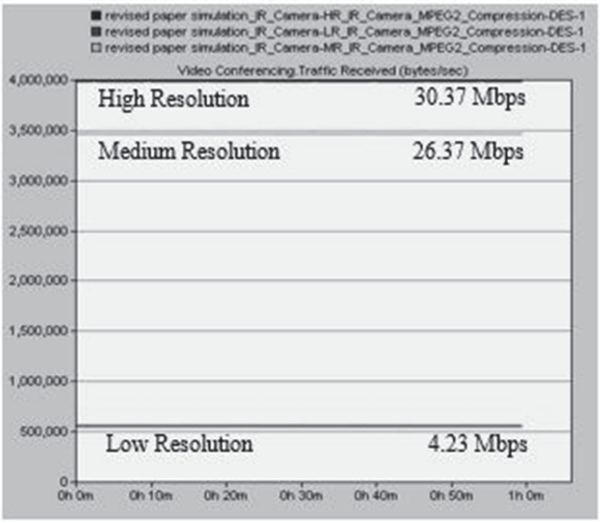

Fig. 9. Amount of data received with MPEG-2

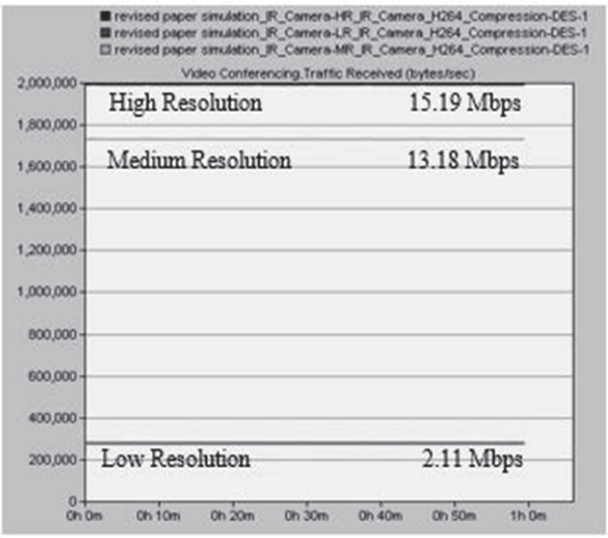

Fig. 10. Amount of data received with H.264

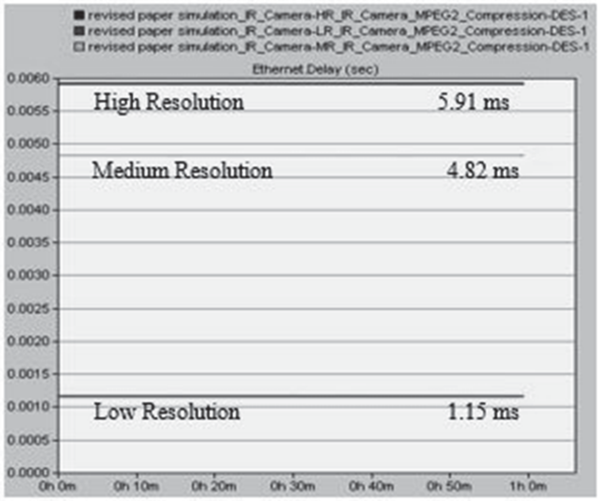

Fig. 11. End-to-end delay with MPEG-2

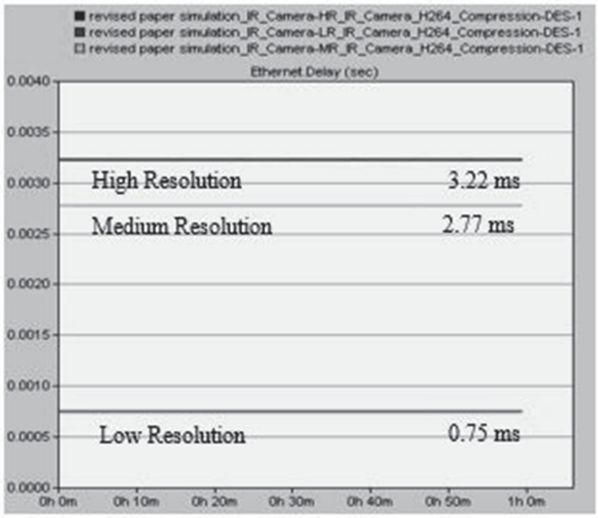

Fig. 12. End-to-end delay with H.264

V. Conclusion

In this paper, we proposed communication network architecture for WT monitoring and control based on IR-camera. We studied the feasibility of IR-camera for monitoring and control of WT in real-time. Therefore, several factors such as the type of fault and risk associated with the components of WT are considered. In this way, the different components of WT are categorized into low, medium, and high priorities for monitoring with an IR-camera. The communication network was designed in two parts the internal communication network inside the WT and the external communication network between WT and remote control center. Based on reference papers two different analysis techniques such as quantitative and qualitative were briefly discussed. The amount of data traffic was then numerically modeled with different parameters for IR video stream transmission, such as color depth sensors, resolutions, frame size, frame number, and data rates. The communication network architecture was implemented through OPNET. The performance of communication network was analyzed by considering meteorological mast and IR-cameras with different resolutions: low (160*120), medium (320*240), and high (384*288). The simulation results were verified by comparing the numerical calculation with the amount of receiving data at the WTC and the control center server. The network latency of data transmission from meteorological mast and IR-cameras were recorded. The end-to-end delay was analyzed for the IR-camera by considering without compression and with MPEG-2 and H.264 compression techniques. The end-to-end delay without compression was 2.2 ms, 14.5 ms, and 16.7 ms for low, medium, and high resolutions, respectively. The communication channel capacity was utilized for other traffic of different applications, by considering H.264 and/or MPEG-2 compression. The results can satisfy the IEEE 1646 standard communication delivery time performance requirements for WT monitoring and control system with IR-camera. In future, the work will be extended for wind power farm.

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