Wireless Network Architecture for Cyber Physical Wind Energy System

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ABSTRACT There is a growing interest to increase the grid integration of large-scale wind power farms (WPF). As most WPFs are located in remote areas where abundant wind resources are available, these sites are lacking communication infrastructures and network coverage which present major obstacles in enabling reliable data transmission between WPFs and their control centers. With the absence of unified communication network architecture, different vendors and manufacturers are developing their own monitoring and control solutions according to their needs. There is a knowledge gap related to the design of WPF communication networks, where the assumptions of available articles do not represent the complete monitoring data from WPF subsystems including wind turbines, meteorological towers and substations. This work aims to design a wireless network architecture for the grid integration of cyber physical wind energy system based on the IEC 61400-25 standard. The proposed architecture consists of four layers: a wind farm layer, a data acquisition layer, a communication network layer and an application layer. Wireless communication technologies outperform conventional wired-based solutions by offering lower costs, greater flexibility and easier deployment. Based on IEC 61400-25 standard, a wireless turbine area network is proposed for collecting sensing data from wind turbine parts, and connected to a wireless farm area network developed for communication between the remote control center and wind turbines. The network performance of the proposed wireless wind turbine internal network (includes the number of sensor nodes, data types and data size) is evaluated considering different wireless technologies (ZigBee, WiFi and WiMAX) in view of end-to-end delay, wireless channel capacity, and data loss. The simulation results show that wireless-based solutions can meet the delay requirements of the IEEE 1646 standard. This work contributes for building a redundant wireless communication infrastructure for remote monitoring of WPFs with scalable coverage and capacity.

INDEX TERMS IEC 61400-25, WiFi, WiMAX, wind farm, wind turbine, wireless communication network, ZigBee.

I. INTRODUCTION Renewable energy sources (RES) have been emerged as a new paradigm to fulfill the demands for more electricity generation due to limited fossil fuel resources and the environmental concern regarding CO2 emissions. Increasing attention has been directed toward various RES including hydro, solar, wind, geothermal, tidal, wave and biomass. By the end of 2017, the global generation capacity from renewable was about 2,179 GW including hydropower, wind, solar, bioenergy and geothermal. The largest share was the hydropower with an installed capacity of about
1,152 GW, while the remainder accounted for wind, solar, bioenergy, geothermal and marine energy with capacities of about 514 GW, 397 GW, 109 GW, 13 GW and 500 MW, respectively [1]. Electricity generation from wind energy has received much attention among various RES, and many countries are planning/building large-scale wind power farms (WPF) [2], [3]. In Saudi Arabia, the government has set an ambitious plan for electricity generation from RES. Sakaka solar PV power plant (300 MW) and Dumat Al Jandal onshore wind project (400 MW) are among the planned renewable energy projects. The Dumat Al Jandal wind project will be the first large-scale onshore WPF in Saudi Arabia which is expected to be in operation by 2022, generating enough power to supply 70,000 homes [4].

A typical WPF consists of many turbines installed over a large geographical area. As most of the WPFs are constructed in remote sites with abundant wind resources, these sites are lacking communication infrastructures and network coverage. With the direction toward increasing the penetration rate of large-scale WPFs, the communication network will play an important role in monitoring, operating and protecting for wind turbines and the electric power system [5]. With the grid integration of large-scale WPFs, the monitoring scope is expanding from monitoring the operation of individual wind turbines to cover the whole WPF subsystems including electrical connections, protection systems and meteorological towers. A huge amount of monitoring data and measurements are generated from WPF subsystems that need to be communicated with the control center causing more burden on the communication infrastructures [2].

Different solutions are available for real-time monitoring and control of WPFs including energy management systems (EMS), supervisory control and data acquisition (SCADA) system, condition monitoring system (CMS) and structure health monitoring (SHM). These systems aim to detect and isolate any fault/failure before causing catastrophic problems. Authors in [6] provided a survey on WPF communication networks where several communication technologies including wired and wireless solutions are used to support the operation of WPFs. Wired communication technologies include wired local area network (LAN), telephone line, fiber optic and propriety data communication, while wireless technologies include ZigBee, WiFi, World Interoperability for Microwave Access (WiMAX), satellite and digital microwave [5], [6]. However, issues related to network bandwidth, latency, reliability, and security should be considered when designing a communication infrastructure for a WPF.
TABLE 1. Comparison among previous research work.

| Reference | WPF Type       | Communication Technology       | Wireless | Comments |
|-----------|----------------|--------------------------------|----------|----------|
|           |                | Wired                         |          |          |
| [5]       | Offshore WPF   | Ethernet, Fiber Optic, Modbus/DNP3, Phone Line, Internet | ✗        | Authors described the SCADA communication system for Bear Mountain WPF in British Columbia, Canada (34 wind turbines, 102 MW) |
| [7]       | Offshore WPF   | Ethernet, Fiber Optic         | WiMAX    | Authors explained the communication network topology used for the Horns Rev offshore wind farm in Denmark (80 wind turbines, 160 MW) |
| [8]       | Offshore WPF   | Ethernet, Fiber Optic         | ✗        | Authors provided a general description for the communication infrastructures in the Greater Gabbard wind project (140 wind turbines, 504 MW) |
| [9]       | Onshore WPF    | Ethernet                       | ✗        | Authors developed a condition monitoring and control system for the Yeong Heung wind farm in South Korea (9 wind turbines, 22 MW) |
| [12]      | Offshore WPF   | Ethernet, SDN                  | ✗        | Authors demonstrated the economic profits for the software-defined networking (SDN) compared to the conventional Ethernet-based architectures considering a case study of a WPF in Northwestern Europe |
| [13]      | Onshore WPF    |                                 | WiMAX    | Authors studied the applications of WiMAX in monitoring WPFs. This work considered a case study of a wind farm consists of 33 wind turbines and a remote monitoring center using NS-2 Simulator. |
| [20]      | Offshore WPF   | EPON                          | ✗        | Authors proposed communication network architecture for smart WPFs based on Ethernet passive optical network (EPON). |
| [21]      | Offshore WPF   |                                 | ✗        | Authors developed a hybrid energy management system (EMS) to determine the set points of wind turbines and optimize the WPF operation. However, the communication delay and the underlying communication infrastructure (wired/wireless) for information sharing among transmission system operator (TSO), cluster EMS, and wind turbines have not been investigated. |
| [22]      | Offshore WPF   |                                 | ✗        | Authors reviewed control architectures in large scale offshore WPFs and highlighted the impact of the communication network in WPF control. |
| [23]      | Offshore WPF   | Ethernet                       | ✗        | Authors proposed a framework for a cyber physical wind energy system. The communication network was configured based on conventional Ethernet-based architecture considering different wind turbine operation modes (idle, start-up, power generation and shutdown). This work considered a case study of Southwest offshore WPF located in South Korea (20 WTs, 60 MW). |
| [10][11]  | Onshore Wind Turbine TAN (24 sensor nodes) | Ethernet | ✗        | Authors designed a data acquisition (DAQ) platform for CMS in a real wind turbine in Hare Hill, Scotland (Vestas V47, 660kW). |
| [14]      | Onshore Wind Turbine TAN (9 sensor nodes) | ✗        | LoRa-WAN | Authors designed a CMS for a wind turbine based on a wireless low-power wide-area network (LoRa-WAN) technology. The system consists of sensor devices, a gateway and a network server. |
| Present Work | Onshore Wind Turbine TAN (102 sensor nodes) | Ethernet | ZigBee, WiFi, WiMAX | Propose a wireless communication model for the wind turbine internal network. Different wireless communication technologies including ZigBee, WiFi and WiMAX have been evaluated for a wind turbine (Vestas V150-4.2 MW) and compared with conventional Ethernet-based architecture. |

* Available information for real WPF projects shows a high level overview for the communication infrastructure but detailed network description and implementation are not publicly accessible.

TAN: Turbine Area Network

Authors in [5]–[9] explained briefly about the communication infrastructure in real WPF projects. Authors in [5] described the SCADA communication system for Bear Mountain WPF in British Columbia, Canada (34 wind turbines, 102 MW) including wind turbines, process data interface, grid data acquisition and substation control unit. Authors in [7] explained the communication network topology used for the remote monitoring system in Horns Rev offshore wind farm in Denmark (80 wind turbines, 160 MW). The communication network consists of 1 Gigabit single-mode optical fibers between wind turbines and the offshore platform, and a secondary wireless solution of 34 Mbit radio
link between the offshore platform and the local control center. Authors in [8] discussed the design consideration for Ethernet-based communication network in large-scale WPFs and provided a general description for the communication infrastructures in the Greater Gabbard wind project (140 wind turbines, 504 MW). Authors in [9] developed a condition monitoring and control system for the Yeung Heung wind farm in South Korea (9 wind turbines, 22 MW). The developed CMS has been installed at the nacelle and all turbines have been connected to the control center via a dedicated Ethernet network. Although references [5]–[9] are good examples of the communication infrastructure in real WPFs, limited information has been given regarding how to design a WPF communication network, different communication topologies, network size or future expansions.

Generally, the WPF communication network can be divided into two parts: wind turbine internal network and wind farm external network. Both wired and wireless communication technologies could be used for internal/external network. Considering the wired-based solutions, authors in [10], [11] described the requirements of a wind turbine condition monitoring system and discussed the installation of the CMS in a real wind turbine (Vestas V47). The CMS consists of a data acquisition system located in the nacelle and connected through a fiber optical link to a data storage device located in the base of the tower. The monitoring parameters include vibration, current, voltage, temperature, rotor speed, wind speed, wind direction, tower movement and atmospheric pressure. Authors in [12] discussed the wind farm communication network based on software-defined networking (SDN) and network function virtualization (NFV). This work demonstrated the economic profits for the proposed solution compared to the conventional Ethernet-based architectures considering a case study of a WPF in Northwestern Europe. Considering the wireless-based solutions, authors in [13] studied the applications of WiMAX in monitoring WPFs. This work considered a case study of a wind farm consists of 33 wind turbines and a remote monitoring center. The simulation results showed the time delay and data loss between wind turbines and the remote monitoring station using NS-2 Simulator. Authors in [14] designed a CMS for a wind turbine based on a wireless low-power wide-area network (LoRa-WAN) technology. The system consists of sensor devices, a gateway and a network server. The monitoring parameters include three phase-currents, three-phase voltages, power and power factor. Considering [10]–[14], these studies considered only a single wired/wireless solution inside the wind turbine or among wind turbines and the
control center. However, the assumptions for the sensor data do not represent the complete monitoring data from wind turbine/WPF subsystems.

Recently, the applications of the internet of things (IoT) and the cyber physical systems (CPS) technology have received great attention in various smart grid domains including generation, transmission, distribution and consumption. IoT and CPS can support the smart grid by incorporating smart sensors and actuators devices, smart information collection systems, smart communication technologies, and smart applications [15]–[19]. The advanced development and mature in smart sensors and communication technologies are considered the main driver for enabling the future smart WPFs [20]. In smart WPFs, wind turbines will able to sense, analyze, decide and control individually or incorporation with other wind turbines through two-way communications. Furthermore, through smart embedded devices, smart wind turbines will be able to interact with the internal or external environment and adjust their operation with the aim to maximize the WPF generation, availability and lifetime without human intervention.

Considering previous research work, most research articles studied the communication networks for WPFs where researchers focused on describing the communication solutions used in real wind farm projects [5]–[9], while others studied the feasibility of a single wired/wireless solution inside wind turbine [10], [11] or among wind turbines and the control center [12]–[14]. However, there is limited research work and a knowledge gap related to the design of WPF communication networks, where the assumptions in available articles with few sensor nodes do not represent the complete monitoring data from WPF subsystems including turbines, meteorological towers and substations. As the WPF communication network will play an important role in the future energy management system [21] and the control of large-scale WPF [22], this work aims to fill this knowledge gap by providing a reference network model and simulation for wind turbine internal network based on IEC 61400-25 standard. To the best of our knowledge, this is the first work that investigates and compares the performance of four different communication technologies including Ethernet, ZigBee, WiFi and WiMAX for a wind turbine. Table 1 presents a comparison among previous related work. The main contributions of this work are:

- Propose a framework for the wireless cyber physical wind energy system. It consists of four layers: a wind farm layer, a data acquisition layer, a communication network layer and an application layer.
- Propose a wireless communication model for the wind turbine internal network based on IEC 61400-25 standard and define data types, data size and the number of sensor nodes inside the wind turbine.
- Build communication network models for the wind turbine internal network using OPNET Modeler and

![Figure 3. Wireless cyber physical model for wind turbine internal network.](image-url)
evaluate the network performance with respect to end-to-end delay and data loss for different communication technologies including ZigBee, WiFi and WiMAX.

The rest of the paper is structured as follows. Section 2 presents the framework for the cyber physical wind energy system. Section 3 describes the proposed wireless network architecture for WPF. In Section 4, the network modeling and assumptions are given. Section 5 provides a detailed performance evaluation and simulation results for different wireless communication technologies. Finally, Section 6 introduced the conclusions.

II. CYBER PHYSICAL WIND ENERGY SYSTEM

The WPFs are complex cyber physical systems due to the coupling between the electric power system and the information and communication technology (ICT). The word “physical” means the physical elements in the WPF such as wind turbines, transformers, meteorological masts, substation, etc. while the word “cyber” means using smart sensors/actuators nodes, smart communication networks and smart applications that enable real-time monitoring and control of the physical WPF elements. Figure 1 shows the proposed multilayer architecture for the cyber physical wind energy system. The architecture is divided into four layers: a wind farm layer, a data acquisition layer, a communication network layer and an application layer [23].

A. WIND FARM LAYER

The main elements of the WPF are wind turbines, transformers, electrical collection system, a substation and a connection to the grid. There are different electric topologies (radial, ring and star) based on the WPF size and the level of reliability.

B. DATA ACQUISITION LAYER

The data acquisition layer interacts with the physical elements of the WPF through smart sensors/actuators. Different sensor nodes and measurement devices are deployed to collect real-time monitoring data from the WPF subsystem and transmit it to the upper layer through the communication network layer.

TABLE 2. Description of logical nodes of a wind turbine based on IEC 61400-25-2.

| Standard | Logic Node         | Description               |
|----------|--------------------|---------------------------|
| IEC 61400-25 | WROT   | Wind Turbine Rotor Information |
|          | WTRM   | Wind Turbine Transmission Information |
|          | WGEN   | Wind Turbine Generator Information |
|          | WCNV   | Wind Turbine Converter Information |
|          | WYAW   | Wind Turbine Yawing Information |
|          | WTRF   | Wind Turbine Transformer Information |
|          | WNAC   | Wind Turbine Nacelle Information |
|          | WMET   | Wind Power Meteorological Information |

TABLE 3. Different wireless communication technologies for WPFs.

| Technology | Standard | Description                        |
|------------|----------|------------------------------------|
|            | Standard | IEEE 802.15.4                      |
| ZigBee     | Data Rate | 250 kbps                           |
|            | Coverage Range | 10-75 m                            |
|            | Application Zone | Wind turbine, Substation           |
|            | Advantages     | Low power consumption, low cost    |
| Wi-Fi      | Data Rate     | 11-300 Mbps                        |
|            | Coverage Range | 100 m (indoor)                     |
|            | Application Zone | Wind turbine, Substation          |
|            | Advantages     | High speed, mature standards       |
| WiMAX      | Data Rate     | 92 Mbps                            |
|            | Coverage Range | 9 km                               |
|            | Application Zone | Wind farm                     |
|            | Advantages     | Low cost, low latency              |
| Cellular   | Data Rate     | 4G-LTE                             |
|            | Coverage Range | 300 Mbps, 3 Gbps (LTE-advanced)   |
|            | Application Zone | Wind farm                     |
|            | Advantages     | High data rate                     |

TABLE 4. Wind turbine analogue measurements and status information.

| Logical Node | Number of analogue Measurements | Number of status Information |
|--------------|---------------------------------|----------------------------|
| WROT         | 9                               | 5                          |
| WTRM         | 10                              | 8                          |
| WGEN         | 12                              | 2                          |
| WCNV         | 12                              | 2                          |
| WTRF         | 9                               | 3                          |
| WNAC         | 8                               | 4                          |
| WYAW         | 5                               | 2                          |
| WTRW         | 1                               | 3                          |
| WMET         | 7                               | 0                          |
| Total        | 73                              | 29                         |

C. COMMUNICATION NETWORK LAYER

The communication network is the most important layer which includes various wired/wireless communication technologies and various network devices. Two-way communications are needed to enable data exchange among different WPF applications. The communication network layer receives the monitoring data from sensor nodes and measurement devices in the data acquisition layer and transmits it to the upper layer. Also, it delivers the control commands from the control center to the actuators in the lower layer.

D. APPLICATION LAYER

The application layer is the top layer where received monitoring data is processed and analyzed to support various WPF services. There are different servers at the control center such as historical servers, SACAD server, meteorological server, metering server, etc. The received monitoring data enables the control center operator to manage the WPF operation as well as making decisions and sending control commands accordingly.
A. DATA MODEL FOR WIND TURBINE BASED ON IEC 61400-25 STANDARD

The IEC 61400-25 standard defines the information models and information exchange models for monitoring and control of WPFs. Based on IEC 61400-25-2 [24], it is assumed that a wind turbine consists of nine logical nodes: WROT, WTRM, WGEN, WCNV, WTRF, WNAC, WYAW, WTOw, and WMET, as shown in Equation (1).

$$\text{WT}_{LN} = \{\text{WROT}, \text{WTRM}, \text{WGEN}, \text{WCNV}, \text{WTRF}, \text{WNAC}, \text{WYAW}, \text{WTOw}, \text{WMET}\}$$

(1)

Each logical node contains different types of information including analogue measurements and status information. The total number of measurements is given in Table 4. The full descriptions of analogue measurements and status information inside wind turbine are given in Appendix.

Figure 3 shows the wireless cyber physical model for wind turbine internal network. Different types of sensor nodes and measurement devices are connected to different wind turbine parts for measuring different parameters, such as voltage (V), current (I), rotor speed (RotSpd), rotor position (RotPos), hub temperature (HubTmp), humidity (Hum), etc. Equation (2) defines types of sensor nodes $S_{N_{TYPE}}$ inside a wind turbine subsystem.

$$S_{N_{TYPE}} \subseteq \{V, I, \text{RotSpd}, \text{RotPos}, \text{HubTmp}, \text{Hum}, \ldots\}$$

(2)

Each sensor node $S_{N_{i}}$ is identified by an identification number $S_{N_{ID}}$ and the physical location $W_{T_{LN}}$ inside the wind turbine, as given in Equation (3).

$$S_{N_{i}} = \{S_{N_{ID}}, W_{T_{LN}}, S_{N_{TYPE}}\}$$

(3)
Based on the sampling rate $F_s$, the sample size $N_B$ and the number of channels $N_C$, the data rate (amount of data generated from each sensor, $SN_{DR}$) is calculated based on Equation (4).

$$SN_{DR} = N_B \times F_S \times N_C$$ (4)

Based on IEC 61400-25, a list of the monitoring parameters inside the wind turbine and the amount of data generated from wind turbine subsystems are given in Table 5.

### B. DATA MODEL FOR WIND FARM PROTECTION BASED ON IEC 61850

There are different topologies for connecting wind turbines to the collector feeder such as radial feeder, bifurcated radial feeder, feeder sub-feeder and looped feeder. The selection among these topologies is based on the WPF size and the level of reliability [29]–[31]. The WPF is divided into different protection zones such as wind turbine zone, collector feeder zone, collector bus zone and HV transformer zone. Each protection zone includes one or more of the protection devices. These multifunction protection devices are installed in order to provide electrical fault protection.

Figure 4 shows a single line diagram of a WPF. Each wind turbine is connected to a step-up transformer to step-up the voltage, and all feeders are connected to the power grid through a high voltage transformer. There are three different types of IEDs: CB IED, MU IED and P&C IED. The main function of the MU IED is to acquire the voltage and the current while the P&C IED executes all protection and control requirements. The wind turbine generator, the collector feeder and the collector bus could be represented with one CB-IED, one MU-IED and one P&C IED. Table 6 shows the configuration of IEDs at different WPF zones.

![Wireless cyber physical model for wind farm substation.](image)

**TABLE 5. Monitoring parameters of a wind turbine based on IEC 61400-25.**

| Logical Node | Monitoring Parameters | # of Sensors | Data Rate bytes/s |
|--------------|-----------------------|--------------|-------------------|
| WROT         | Speed, Position, Temperature, Pressure, Pitch angle, Status | 14           | 642               |
| WTRM         | Temperature, Vibration, Oil level, Grease level, Pressure, Status | 18           | 2,828             |
| WGEN         | Speed, Power, Temperature, Voltage, Current, Status | 14           | 73,764            |
| WCNV         | Frequency, Torque, Temperature, Voltage, Current, PF, Status | 14           | 74,060            |
| WTRF         | Oil level, Voltage, Current, Temperature, Status | 12           | 73,740            |
| WNAC         | Orientation, Wind speed, Wind direction, Temperature, Humidity | 12           | 112               |
| WYAW         | Speed, position, Temperature, Grease level, Pressure | 7            | 220               |
| WTOW         | Humidity, Status | 4            | 8                 |
| WMET         | Wind speed, Wind direction, Temperature, Pressure, Humidity | 7            | 228               |
| **Total number of monitoring parameters** | **102** | **225,602** |
C. DATA MODEL FOR METEOROLOGICAL MAST

In order to measure the environmental condition, one or more meteorological masts are installed for collecting meteorological data [32], [33]. The tower is equipped with different sensors and measuring instruments mounted at several heights to measure parameters such as humidity, ambient temperature, wind speed, wind direction, rain detection and atmospheric pressure. Examples of the measurement instruments are wind vanes, anemometers, barometers, and rain sensors. Each meteorological tower has a control unit located at the base of the tower where communication cables are connected between sensor nodes and the control unit.

Table 7 lists types of sensor nodes and measurement devices installed at the meteorological tower. Please note that there are different types of meteorological towers with various heights for onshore/offshore environments where

| Location | Sensor Type | Sampling Rate | Data Rate |
|----------|-------------|---------------|-----------|
| 95 m     | Anemometer  | 3 Hz          | 6 bytes/s |
| 95 m     | Wind Vane   | 3 Hz          | 6 bytes/s |
| 95 m     | Temperature | 1 Hz          | 2 bytes/s |
| 95 m     | Humidity    | 1 Hz          | 2 bytes/s |
| 95 m     | Air Pressure| 100 Hz        | 200 bytes/s |
| 85 m     | Anemometer  | 3 Hz          | 6 bytes/s |
| 85 m     | Wind Vane   | 3 Hz          | 6 bytes/s |
| 85 m     | Humidity    | 1 Hz          | 2 bytes/s |
| 50 m     | Anemometer  | 3 Hz          | 6 bytes/s |
| 50 m     | Wind Vane   | 3 Hz          | 6 bytes/s |
| 10 m     | Anemometer  | 3 Hz          | 6 bytes/s |
| 10 m     | Humidity    | 1 Hz          | 2 bytes/s |
| 10 m     | Air Pressure| 100 Hz        | 200 bytes/s |
| 10 m     | Rain sensor | 4 Hz          | 8 bytes/s |

Total amount of monitoring data 458 bytes/s

TABLE 6. Configuration of IEDs at different WPF zones.

| Zone            | IED Type | Data Type & Data size            |
|-----------------|----------|----------------------------------|
| Wind Turbine    | CB IED   | Breaker Status, 16 bytes         |
|                 | MU IED   | 3-Phase V & I, 76,800 bytes      |
|                 | P&C IED  | Control                          |
| Collector Feeder| CB IED   | Breaker Status, 16 bytes         |
|                 | MU IED   | 3-Phase V & I, 76,800 bytes      |
|                 | P&C IED  | Control                          |
| Collector Bus   | CB IED   | Breaker Status, 16 bytes         |
|                 | MU IED   | 3-Phase V & I, 76,800 bytes      |
|                 | P&C IED  | Control                          |

FIGURE 5. Wireless cyber physical model for met mast.
different numbers of sensor nodes and measurement devices are located at different levels. Data received from sensor nodes and measuring instruments are stored locally at the meteorological tower control unit and transmitted to the control center through the communication network.

V. NETWORK MODELING AND SIMULATION RESULTS

This work considers Dumat Al-Jandal WPF as a case study. Dumat Al-Jandal (400 MW) is the first large-scale onshore WPF in Saudi Arabia located in Al Jouf region, north of Riyadh and expected to be in operation by 2022. The WPF will consist of 99 wind turbines (Vestas V150-4.2 MW) [34], [35]. Considering the specifications of Vestas V150-4.2, the turbine blade length and the rotor diameter are 73.7m and 150m, respectively. The nacelle dimensions are 6.9m × 12.8m × 4.2m for height, length, and width. This work focuses on the design of the wireless turbine area network. Three different communication technologies are considered: ZigBee, WiFi and WiMAX. Table 8 shows a summary of different simulation scenarios.

A. ZIGBEE-BASED TURBINE AREA NETWORK

The performance of the ZigBee-based wind turbine internal network is evaluated using OPNET Modeler. There are two types of nodes in ZigBee-based architecture: ZigBee end devices (ZBE) and ZigBee coordinator (ZBC). The ZBEs are configured to collect monitoring data from different wind turbines parts and transmit it to the ZBC. The ZBC transmits the monitoring data to the wind turbine controller located at the nacelle. The network topology is configured as a star topology. Two scenarios are considered: a single ZBC and multiple ZBC, as shown in Fig. 6. In scenario (1), with a single ZBC, the wind turbine internal network represents a single personal area network (PAN). The network is configured with a single ZBC and 102 ZBEs. In scenario (2), with multiple ZBCs, the wind turbine is configured with 9 subnetworks where each subnetwork represents an isolated network. The communication network is configured with 9 ZBCs and 102 ZBEs. The number of sensor nodes and the amount of generated sensing data for different sensor nodes are given in Table 5. The following metrics have been considered for performance evaluation:

- ZigBee Traffic received (bits/s): it represents the traffic received by this node at the application layer.
- ZigBee end-to-end delay (s): it represents the total delay between creation and reception of application packets.

Figure 7 shows the received traffic for the ZigBee-based internal network with multiple coordinators. The simulation results show that three subnetworks (PAN3 (WGEN), PAN4 (WCNV) and PAN8 (WTRF) were not able to receive the monitoring data from ZBEs. These three subnetworks include voltage and current sensors with high-speed sensing data transmission. The amount of sensing data from the voltage and current sensors is about 589,824 bps which is beyond the capability of ZigBee with a maximum data rate of 250 kbps. As a result, the wind turbine internal network using ZigBee configuration was not able to support the full data transmission of 102 sensor nodes in scenario (1). In scenario (2), excluding the voltage and current sensors, the wind turbine internal network is configured with 84 sensor nodes. Figure 8 shows the received traffic for ZigBee-based architecture for scenario (2). The total traffic received for the wind turbine internal network is approximately 35,344 bps. The traffic received for PAN1, PAN2, PAN3, PAN4, PAN5, PAN6, PAN7, PAN8, and PAN9 are 5,136 bps, 22,624 bps, 288 bps, 2,656 bps, 896 bps, 1,760 bps, 64 bps, 96 bps and 1,824 bps, respectively.

Simulation results showed that the received traffic in scenario (2) agrees with the calculation gained for both single coordinator and multiple coordinators. Figure 9a shows the end-to-end (ETE) delay for ZigBee-based architecture with a single coordinator. The ETE delay was approximately 9.6 ms. In Figure 9b, the ETE delay for multiple coordinators scenario was approximately 3.48 ms, 9.92 ms, 2.15 ms, 3.99 ms, 2.31 ms, 3.02 ms, 2.08 ms, 2.07 ms, and 3.05 ms for PAN1-WROT, PAN2-WTRM, PAN3-WGEN, PAN4-WCNV, PAN5-WNAC, PAN6-WYAW, PAN7-WTOW, PAN8-WTRF, and PAN9-WMET, respectively. The highest delay value of PAN2 for WTRM is due to a large amount of sensing data compared with other logical nodes.

B. WIFI-BASED TURBINE AREA NETWORK

The WiFi-based wind turbine internal network is configured with 102 sensor nodes and a wireless front-end device.

\[\text{Figure 6. ZigBee-based wind turbine internal network.} \]

\[\text{Table 8. Simulation scenarios.} \]

| Section | Network Segment | Technology | Direction/ Period |
|---------|-----------------|------------|------------------|
| A       | Turbine Area Network | ZigBee | Uplink/ Continuous |
| B       | Turbine Area Network | WiFi | Uplink/ Continuous |
| C       | Farm Area Network | WiMAX | Uplink/ Continuous |
| D       | Turbine Area Network | Ethernet | Uplink/ Continuous |

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FIGURE 7. Received traffic for ZigBee-based architecture with 102 sensor nodes. (a) PAN 1-WROT. (b) PAN 2-WTRN. (c) PAN 3-WGEN. (d) PAN 4-WCNV, (e) PAN 5-WNAC, (f) PAN 6-WYAW, (g) PAN 7-WTOW, (h) PAN 8-WTRF, and (i) PAN 9-WMET.

(Wireless Server), as shown in Fig. 10. Each sensor node is represented with a wireless workstation (wlan_wkstn_adv) and the communication topology is configured in an infrastructure mode. The number of sensor nodes and the amount of generated sensing data for different wind turbine parts are configured based on Table 5. The following metrics have been considered for the performance evaluation:

- Server FTP Traffic received (bytes/s): it represents the average bytes per second forwarded to all FTP applications by the transport layers in the server node.
- Wireless LAN Delay (s): it represents the end to end delay of all the packets received by the wireless LAN MACs of all WLAN nodes in the network and forwarded to the higher layer.

Two data rates are considered for WiFi-based architecture: 24 Mbps and 54 Mbps. The simulation results, which are shown in Fig. 11, show that the monitoring data are received successfully for both data rates. The total traffic for the wind turbine internal network was approximately 225,602 bytes/s. The traffic received for sensor nodes such as displacement, pitch angle, speed and humidity were 80 bytes/s, 36 bytes/s, 18 bytes/s, and 6 bytes/s, respectively. Figure 12 shows the average wireless LAN delay for the wind turbine area network was approximately 1.25 ms and 0.89 ms for a data rate of 24 Mbps and 54 Mbps, respectively.

C. WIMAX BASED TURBINE EXTERNAL NETWORK

The performance of the wireless farm area network is evaluated using WiMAX technology. In this scenario, the communication network model is configured for one wind turbine, one meteorological tower and one protection and control (P&C) IED. Figure 13 shows the WiMAX-based OPNET model for WPF external network. The communication network consists of a wind turbine, a meteorological tower, a P&C IED, a base station and a server. The distance between the base station and the wind turbine/meteorological tower is configured with about 3 km.

The detailed description of the OPNET model is given in Table 9. Each wind turbine with its sensors is represented by a subscriber station (SS) sending information to the control center and receiving the control commands. First, the application definition has been configured for sending monitoring data with file transfer protocol (FTP) including inter-request time (the time in second between consecutive FTP requests) and file size (file in bytes of the FTP file to be transferred).
Then, the profile definition and WiMAX configuration have been configured. The configuration parameters for data types and the amount of traffic for WiMAX scenarios are summarized in Table 10 and the WiMAX simulation parameters are given in Table 11.

Figure 14 shows the received traffic at the control center server. The received traffic for analogue measurement, status data, protection IED and meteorological mast were about 225,544 bytes/s, 58 bytes/s, 76,816 bytes/s and 458 bytes/s, respectively. The received traffic at the control center agrees with the configured data given in Table 10.
WiMAX delay represents the end-to-end delay of all the data packets that are successfully received by the WiMAX MAC and forwarded to the higher layer. Figure 15 shows the WiMAX delay of about 0.527 ms, 6.71 ms and 7.55 ms for meteorological data, protection data and wind turbine data, respectively.

IP end-to-end delay (s) is the time taken for the packet to reach its destination. It is measured as the difference between the time a packet arrives at its destination and the creation time of the packet. Figure 16 shows the IP end-to-end delay of about 0.47 ms, 10.54 ms and 11.71 ms for meteorological data, protection data and wind turbine data, respectively.

**D. DISCUSSION**

In order to compare the performance of the proposed wireless turbine area network models, a reference Ethernet-based architecture for the wind turbine internal network has been built based on Ref. [23], as shown in Fig. 17. The Ethernet-based architecture consists of nine logical nodes representing the wind turbine subsystems. Each logical node is configured with different monitoring parameters including analogue measurements and status information, as given in Table 5. The wind turbine includes a wind turbine controller (WTC) that monitors the status of the wind turbine subsystems...
FIGURE 14. Received traffic at the control center server. (a) Analogue measurement (b) Status Information. (c) Protection IED (d) Met. Mast.

continuously through sensor nodes and measurement devices. The dimensions for the nacelle (network coverage) are configured with 12m \times 4m. The monitoring data from logical nodes are connected to the WTC through an Ethernet switch working as a data aggregator inside the wind turbine. The communication link capacity is configured with 10BASET and 100BASET.

FIGURE 15. WiMAX delay for wind turbine, meteorological mast and protection IED.

FIGURE 16. IP end-to-end delay for wind turbine, meteorological mast and protection IED.

TABLE 12. Comparison of simulation results for WTAN and WFAN.

| Technology | Data Rate | Topology | Delay       |
|------------|-----------|----------|-------------|
| Ethernet   | 10 Mbps   | Star     | 0.905 ms    |
|            | 100 Mbps  |          | 0.077 ms    |
|            | 250 kbps  | Single coordinator | Not able to support high transmission data of WGEN, WCVN, WTRF |
|            | 102 SNs   |          |             |
|            | 250 kbps  | Single coordinator | 9.6 ms |
|            | 84 SNs    | Multiple Coordinator | 2.07–9.92 ms |
|            |           |          |             |
| WiFi       | 24 Mbps   | Star     | 1.25 ms     |
|            | 54 Mbps   |          | 0.89 ms     |
| WiFi       | Service   | Wind Turbine | 11.71 ms |
|            | Class     |          |             |
|            | Gold/UGS  | Met. Mast | 0.47 ms     |
|            |           | Protection IED | 10.54 ms |
TABLE 13. Data delivery time required based on IEEE 1646 standard.

| Information Type                  | Internal to Substation | External to Substation |
|-----------------------------------|------------------------|------------------------|
| Protection Information            | 4 ms                   | 8-12 ms                |
| Monitoring and Control Information| 16 ms                  | 1 s                    |
| Operation & Maintenance Information| 1 s                   | 10 s                   |
| Video data                        | 1 s                    | 1 s                    |

Figure 18 shows the total traffic received at the WTC from 102 sensor nodes for Ethernet-based architecture. The total traffic received was about 225,602 bytes/s. All monitoring data from different sensor nodes were received successfully. Figure 19 shows the end-to-end delay considering two link capacities: 10 Mbps and 100 Mbps. The end-to-end delay was about 0.905 ms for a link capacity of 10Mbps while about 0.077 ms for a link capacity of 100 Mbps.

Table 12 shows a comparison of simulation results considering different communication technologies including Ethernet, ZigBee, WiFi, and WiMAX. Although Ethernet-based architecture superior other wireless communication technologies in view latency, WiFi-based architecture showed a better performance with an end-to-end delay of about 0.89 ms for a data rate of 54 Mbps. However, ZigBee-based architecture was not able to support the high data transmission from voltage and current sensors which result in high data loss for monitoring data from logical nodes such as generator, converter, and transformer.

In the electric power system, there are strict requirements for data delivery of different applications. As a result, monitoring data should be transferred within a specific time between wind turbines and the control center [36]. Considering the latency requirements for data delivery in electric power substation automation, Table 13 shows the required data delivery time based on IEEE 1646 standard for different applications including protection, monitoring, and operation [37]. The simulation results show that the delivery time of wind turbine data (analogue measurements and status information), meteorological data and protection data meet the latency requirements defined by IEEE 1646 standard.

Further investigations are required for developing hybrid communication architectures which meet the communication needs of WPFs, instead of using a single communication solution. These hybrid communication architectures should incorporate different wired and wireless communication technologies (Ethernet, ZigBee, WiFi, WiMAX, LTE, LoRa, etc.) and satisfy the system requirements with respect to latency, data loss, network coverage, and cost.

VI. CONCLUSION

Communication infrastructures will play an important role in real-time monitoring and control of large-scale WPFs. This paper proposes a framework for the wireless cyber physical wind energy system which consists of four layers: wind farm layer, data acquisition layer, communication network...
### TABLE 14. Total number of analogue measurements and status information inside wind turbine based on IEC 61400-25.

| Wind turbine rotor information (WROT) | Wind turbine converter information (WCNV) |
|--------------------------------------|------------------------------------------|
| **Analogue information**             | **Analogue information**                  |
| Rotor speed at rotor side            | Frequency value                          |
| Angular rotor position              | Torque value                              |
| Temp. in the rotor hub              | Generator side 3 phase phase-to-phase voltage |
| Pressure of hydraulic pitch system for blade 1 | Generator side 3 phase-to-ground voltage |
| Pressure of hydraulic pitch system for blade 2 | Generator side 3 phase current |
| Pressure of hydraulic pitch system for blade 3 | Generator side 3 phase power factor |
| Pitch angle for blade 1             | Grid side 3 phase phase-to-phase voltage  |
| Pitch angle for blade 2             | Grid side 3 phase-to-ground voltage       |
| Pitch angle for blade 3             | Grid side 3 phase current                 |
| Status information                  | Grid side 3 phase power factor            |
| Status of rotor                     | Temperature inside the converter          |
| Status of blade 1                    | Converter - Grid side temperature         |
| Status of blade 2                    |                                           |
| Status of blade 3                    |                                           |
| Status of pitch control             |                                           |
| Wind turbine transmission information (WTRM) | Wind turbineYawing information (WYAW) |
| Analogue information                | Analogue information                      |
| Temp. of shaft bearing 1            | Yawing speed                              |
| Temp. of shaft bearing 2            | Yawing motor/gear temperature             |
| Temp. of gearbox oil                | Yaw bearing rotation angle                |
| Temp. of shaft brake                | Grease level for lubrication of yaw system |
| Vibration of gearbox 1              | Yaw brake pressure                        |
| Vibration of gearbox 2              | Wind turbine tower information (WTRW)     |
| Gear oil pressure                   | Wind turbine generator information (WGEN) |
| Hydraulic pressure for shaft brake  | Analogue information                      |
| Status information                  | Humidity inside tower                     |
| Status of shaft brake               | Status of lift system                     |
| Status of gearbox lubrication system | Status of de-humidifier                  |
| Status of filtration system         | Status of heat-exchanger                  |
| Status of transmission cooling system|                                           |
| Status of heating system            |                                           |
| Status of oil level in gearbox sump |                                           |
| Status of offline filter            |                                           |
| Status of inline filter             |                                           |
| Wind turbine generator information (WGEN) | Wind turbine nacelle information (WNAC) |
| Analogue information                | Analogue information                      |
| Generator speed                     | Nacelle orientation                       |
| Generator active power              | Wind speed outside nacelle                |
| Generator reactive power            | Wind direction outside nacelle            |
| Temp. measurements for generator stator| Temp. outside nacelle                     |
| Temp. measurements for generator rotor| Temp. inside nacelle                      |
| Generator stator 3 phase phase-to-phase voltage | Humidity inside nacelle                  |
| Generator stator 3 phase phase-to-ground voltage | Analogue information                  |
| Generator stator 3 phase current    | Status of beacon                          |
| Generator rotor 3 phase phase-to-phase voltage | Status of heater for wind sensor         |
| Generator rotor 3 phase phase-to-ground voltage | Status of ice detection                  |
| Generator rotor 3 phase current     | Status of primary/secondary anemometer    |

**Nomenclature:**
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layer and application layer. Detailed wireless network models have been built for the wind turbine internal network. The proposed wind turbine model including the number of sensor nodes, data types, and data size is based on IEC 61400-25 standard. In order to evaluate the performance of the proposed model, simulation models have been developed using OPNET Modeler for different communication technologies including Ethernet, ZigBee, WiFi, and WiMAX. Considering the maximum delivery time requirements of the SCADA data, the developed wireless models of WiFi and WiMAX meet the delay requirements of the IEEE 1646 standard. The ZigBee-based models were capable of supporting the wind turbine internal network while excluding the higher sensing data of voltage and current sensors. This work contributes to design a redundant wireless infrastructure for monitoring remote WPFs. Future work aims to investigate the network performance considering real communication channels with impairments.

APPENDIX

See Table 14.

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