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A Cooperative Decision Algorithm to Enhance the Wireless Link Connectivity of the Offshore Wind-Turbine Power System with Wireless Networks

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Abstract: In general, the condition monitoring system (CMS) with wireless sensor network (WSN) and the wireless USB (WUSB) could be considered as a promising technique to manage the future offshore wind-turbine (WT) power system wirelessly for fully employment of wireless multimedia services. However, it still needs a highly reliable solution to tackle with the wireless link breakage problem caused by offshore capricious climate condition as well as by obstacle of wireless devices. Therefore, in this paper, we suggest a cooperative decision algorithm as to guarantee higher reliability of the supervisory control and data acquisition (SCADA) & CMS's fault diagnosis monitoring operation of the offshore WT power system with WSN-WUSB network. We apply a cooperative decision algorithm for recovering the wireless link disconnection and providing a new link path, based on the proposed Orphan Notification message protocol. This algorithm can intelligently select the transmission path with the better channel conditions and thus, improve the reliability of the network. Simulation result shows that the proposed scheme effectively enhances the wireless link connectivity and the overall network performance.

Keywords: Condition Monitoring System, Decision Algorithm, Fault Diagnosis Monitoring, Wind-Turbine, WSN.

1. Introduction

The supervisory control and data acquisition (SCADA) and condition monitoring system (CMS) of wind-turbine (WT) are very essential to operators for guaranteeing reliable maintenance and increasing operating availability [1]. In general, the CMS are used to monitor the status of operating components of WT such as blades, rotors, gearbox, generator, main bearings and tower. The CMS with wireless sensor network (WSN) has been considered as an efficient monitoring and managing technique, since the remotely controlled sensor nodes of the offshore WT system is capable of lowering operation and maintenance (O&M) costs. Note that the sensor nodes in the offshore WT power system play an important role in collecting energy parameters of wind blades. Thus, CMS with WSN has been considered as a very efficient technique to improve WT availability and reduce the O&M costs.

In advent of high-speed and high-data rate exchange services such audio, video, and thousands of sensing data, the future offshore WT power system could exploit huge amount of data packet (i.e., multimedia data transmission) and thus, it could enable the real-time multimedia service supported SCADA & CMS monitoring system. In order to exchange the high-speed and huge amount of data packets of WTs' in offshore with the control center on land, such WT power system should employ high-speed and high-data rate supported method such as the wireless USB (WUSB) technique.

WUSB is a wireless technology to merge WiMedia with the USB technology for various mobile applications. In general, a WUSB network consists of a WUSB host and WUSB devices. The WUSB host creates and maintains the WUSB channel and WUSB devices are controlled their data communications by a WUSB host. Thus, the mobile WUSB devices form WUSB cluster and a set of host and devices synchronized to each other. The data transmission between WUSB devices is also delivered via WUSB host. The general service targets provided by WUSB protocol are audio/video devices and portable devices with short-range connectivity. However, this communication link could be disconnected since there is the only communication link between the host and device in WUSB protocol. This problem is a channel link breakage problem. If the channel link breakage occurs in a WUSB cluster, the host cannot set up the

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communicating link with the WUSB device. Thus, the guarantee of link connectivity is a critical requirement for the protocol design to ensure a normal functionality of the network [2]. This could be overcome by a well-designed protocol algorithm.

Irrespective of a good protocol design, however, in an offshore WT power system employing wireless networks, the severe offshore environment such as the capricious maritime climate or adverse weather condition between the SCADA & CMS control center should be considered as a serious problem as well as wireless communication link disconnection problem. In general, a wireless communication link disconnection problem in land-mobile wireless communication is mainly occurred by obstacles or mobile devices. It should be noted that an offshore WT power system employing wireless communication network suffer both link disconnection (breakage) problems caused by a severe offshore weather/climate condition and a path loss of wireless communication. Thus, there is a trade-off between the advanced multimedia service performance and the maintenance load of such WT power system with wireless communication.

Therefore, in this paper, we suggest a cooperative decision algorithm as an efficient and reliable solution to tackle with the wireless link breakage problem and thus, enhance the reliability of SCADA & CMS's fault diagnosis monitoring operation. We apply the cooperative decision algorithm for recovering the wireless link disconnection and providing a new communication path, based on the proposed Orphan notification message protocol. The remaining paper is organized as follows: Section II presents the proposed offshore wind turbine power system with WSN-WUSB network considered in this paper, section III presents the proposed cooperative decision algorithm for enhancing wireless link connectivity of the proposed offshore WT power system in section II. Section IV and V presents simulation results, discussion and conclusion.

2. Proposed Offshore Wind Turbine Power System with WSN-WUSB Network

A. Offshore WT Power System with SCADA & CMS

Most WT machines are three-blade units comprising the main components, i.e., blades, rotors, generator, gear box and computer system. The proposed offshore WT power system with SCADA & CMS employing WSN and WUSB network is illustrated in Fig. 1, which is for acquisition and monitoring of wirelessly sensing data by WSN's sensors and aggregating of huge amount of sensing data packets by WUSB devices. Each sensor of WSN is attached to WT's main components such as generator, gear box and computer system, and it sends its operational condition status to the WUSB devices wirelessly.

Note that the future offshore WT power system could provide the real-time multimedia service (the high-speed and high-data rate supported wireless transmission) for SCADA & CMS monitoring system such as video-stream or audio-video data stream service. The WUSB device collects the aggregated sensing data of thousands of WT's components or other parts. As shown in Fig. 1, in the proposed offshore WT power system with SCADA & CMS employing WSN-WUSB wireless network, these sensing data are gathered in WUSB devices and are sent to a WUSB host controlled by SCADA & CMS control center. The main role of this control center is to monitor, analyze and diagnose the aggregated sensing data packets, such that it can decide the operational condition of WT and detect the typical failure events [3-4].

B. Related Works : Intelligent Aglorithm for Offshore WT Power System

In the recent research work, a fuzzy based fault diagnosis algorithm has been studied in order to overcome such failure events intelligently [5]. In other previous research works of [6] and [7], WT power system applying WSN have been considered to increase the reliability of fault diagnosis. In [6], the overall reliability of condition monitoring network based on WSN is focused. In [7], the energy efficient routing protocol associated with structure of wind turbines in WSN multi-hop communication. Moreover, from the mechanical perspective, the intelligent diagnosis algorithm with big data has been dealt with in [8]. Since the proposed WT network architecture in this paper is yet to be considered in other previous research works, this paper focus on the link breakage problem of wireless communication and a reliable solution of the WSN-WUSB wireless network in offshore WT power system with SCADA & CMS.

C. Conventional WUSB Standard Protocol

The WUSB standard utilizes the WiMedia MAC and PHY which define several access methods for accessing

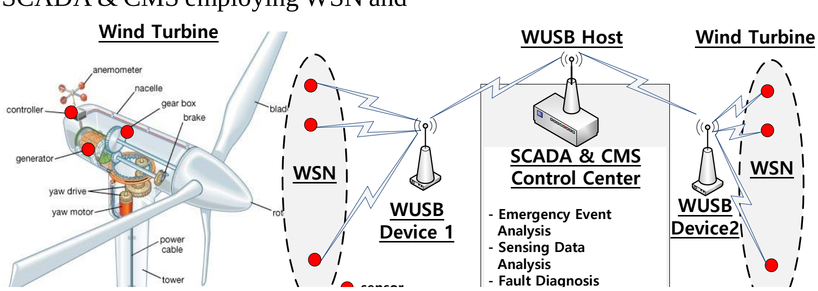

Figure 1. The proposed offshore WT power system with WSN and WUSB networks for monitoring the sensing data of WT components.

the MAC channel, including beacons (for discovery and network management) and distributed reservation protocol (DRP for TDMA type data communications) as shown in Fig. 2 [9].

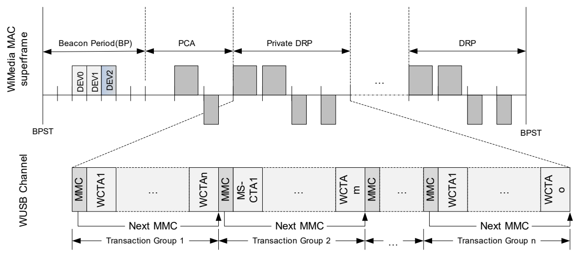

Figure 2. The example of the data exchange between WUSB devices.

The WUSB standard defines a WUSB Channel which is encapsulated within a set of WiMedia MAC super-frames via a set of WiMedia MAC resource reservations (private DRPs). As shown in Fig. 2, the WUSB Channel is a continuous sequence of linked application-specific control packets of MMCs (micro-scheduled management commands), which are transmitted by the host within private DRP reservations of WiMedia MAC. The format of the MMC frame is shown in Fig. 3.

LSB								MSB
Application Identifier	Type	Next MMC Time	Reserved	WUSB Channel Time Stamp	IE[0]	IE[1]	...	IE[n]
2 octets	1 octet	2 octets	2 octets	3 octets	variable	variable	...	variable

Figure 3. The format of the MMC frame.

In Fig. 3, Application Identifier field in the MMC frame are set to indicate WUSB [WUSB (0100H)]. The Type field is used to indicate the MMC Command Type and set to 01H. *Next MMC Time* field indicates the number of microseconds from the beginning of this MMC to the beginning of the next MMC frame. *WUSB Channel Time Stamp* field is set to indicate a time-stamp provided by the host based on a free running timer in the host. The value in this field is set to the clock value of the host when MMC transmission starts. The information element (IE) fields in an MMC are called *Wireless USB Channel_IE* and include protocol time slot allocations, device notification time slot (DNTS), and host information. MMCs contain host identifying information, I/O control structures and a time reference to the next MMC in the sequence. These links provide a continuous thread of control which can be simply followed by devices that join the WUSB cluster. This encapsulated channel provides the structure that serves as the transmission path for data communications between a host and devices in a WUSB cluster.

The WUSB Channel consists of the linked stream of MMCs, which is used to dynamically schedule the channel time for data communications between the host and WUSB devices. The WUSB host periodically broadcasts the MMC to advertise the information of the WUSB channel time allocation (WCTA) and the start of the next MMC. Using the information of the WCTA, WUSB cluster members can communicate with other WUSB devices or the WUSB host. The information of the WCTA is propagated by the wireless USB channel time allocation information element (WCTA_IE) and is included in the MMC frame. Fig. 4 shows its general structure.

LSB					MSB
bLength	IE Identifier (WCTA_IE)	$W_XCTA[0]$	$W_XCTA[1]$	...	$W_XCTA[n]$
1 octet	1 octet	variable	variable	...	variable

Figure 4. The format of the WCTA_IE.

The *bLength* field indicates the total length of the WCTA_IE as shown in Fig. 4. WCTA_IE consists of one or more W_XCTA blocks. There are several types of W_XCTA blocks, and each W_XCTA blocks has a common header including an attribute field and time slot information for Transaction Group. The W_XCTA block describes a time slot allocation relative to the MMC frame. The type of W_XCTA blocks are $W_{DR}CTA$ (device receive), $W_{DT}CTA$ (device transmit), $W_{DNTS}CTA$ (device notification time slot).

D. *Problem Description : Link Breakage Problem in the Offshore WT Power System with WSN-WUSB Network*

The WUSB cluster operates in a star topology, in which the communication is established between devices and a single central controller, called the WUSB host. In this paper, WUSB hosts are deployed at the SCADA & CMS control center for fault diagnosis monitoring operation as shown in Fig. 1. As noted before, the current WUSB wireless communication standard has the severe problem, i.e., the link breakage problem. Such a link breakage problem between the WUSB host and WUSB devices causes the wireless communication disconnection. Moreover, in the offshore WT power system considered in this paper, such link breakage problem should be much worse because of severe offshore weather and climate condition between the SCADA & CMS control center in land and the WT's wireless transmission devices in offshore.

In such a link breakage case of offshore WT power system with WSN-WUSB network, the WUSB host should reconfigure the legacy path between the host and the device. However, the conventional WUSB standard protocol cannot not support the path reconfiguration between host and device. As a result, when the channel impairment between host and device occurs, the WUSB host and device suffering link breakage problem cannot set up a communication link between each other. Fig. 5 shows an example of the data flow and link breakage problem in WUSB transaction. It shows an example of the link data frames to WUSB host and cannot also receive data frames from WUSB host. This link breakage can cause severe problems, but the legacy WUSB protocols do not have addressed this problem. However, if WUSB host can provide a new link path via another WUSB device (i.e., helper device) to WUSB device 2, such link breakage problem can be solved. Therefore, in this paper, we propose a cooperative decision algorithm to provide the new path via another WUSB device to the WUSB device of concern with the channel impairment problem.

3. The Proposed Cooperative Decision Algorithm for Enhancing Wireless Link Connectivity of Offshore WT Power System

A. *Related Works : Wireless Link Disconnectivity Problem*

Research for the network connectivity improvement in WSN also has been conducted in recent years [10-13]. The previous research can improve the network connectivity by deploying one or more nodes in the weakest connectivity area, but they are vulnerable to the link disconnection by the mobility of devices. In [10], authors proposed a deployment algorithm of sensor nodes to guarantee a specified level of multipath connectivity between all nodes. In [14], authors proposed approximation algorithms for deploying relay nodes to create partial vertex connected networks for the cluster heads in WSN.

However, these works focus on deployment of one or more nodes in the weakest connectivity area and do not consider the dynamic link disconnection by the mobility of devices. In [15], authors proposed a new link establishment scheme for the device-to-device communication in the WUSB standard. The proposed scheme can reduce the failure of the reverse link establishment by allocating the resources for the default link and the reverse link simultaneously. In [16], authors proposed a new cooperative MAC protocol for WUSB standard using virtual MIMO links. Based on the channel state information among WUSB devices, the proposed protocol can select the relay path with a higher data rate between the WUSB host and WUSB device as well as between WUSB devices. However, all of these works cannot solve the link disconnection problem by the high mobility or severe channel impairment condition of WUSB devices.

B. *Problem Description : The Different Condition and the Same Solution in Offshore WT Power System with WSN-WUSN Network*

Even though the mobility of WUSB devices in offshore WT power system is not high, such offshore environment could accelerate link disconnection problem because of capricious/adverse maritime weather condition as well as wireless communication channel impairment. Thus, it should be noted that the link breakage problem as illustrated in Fig. 5 is much worse than the previous research works of [10-16]. Finding the solution of link disconnection problem caused by the mobility of devices in WSN is the same goal of finding the solution of link breakage problem in WT power system with WSN-WUSB as illustrated in Fig. 5. Therefore, in this paper, we propose a cooperative decision algorithm employing Orphan Notification message protocol to provide the new path via another WUSB device to the WUSB device of concern and thus, recover the link breakage in the WUSB. Thus, it can enhance the reliability of SCADA & CMS's fault diagnosis monitoring operation.

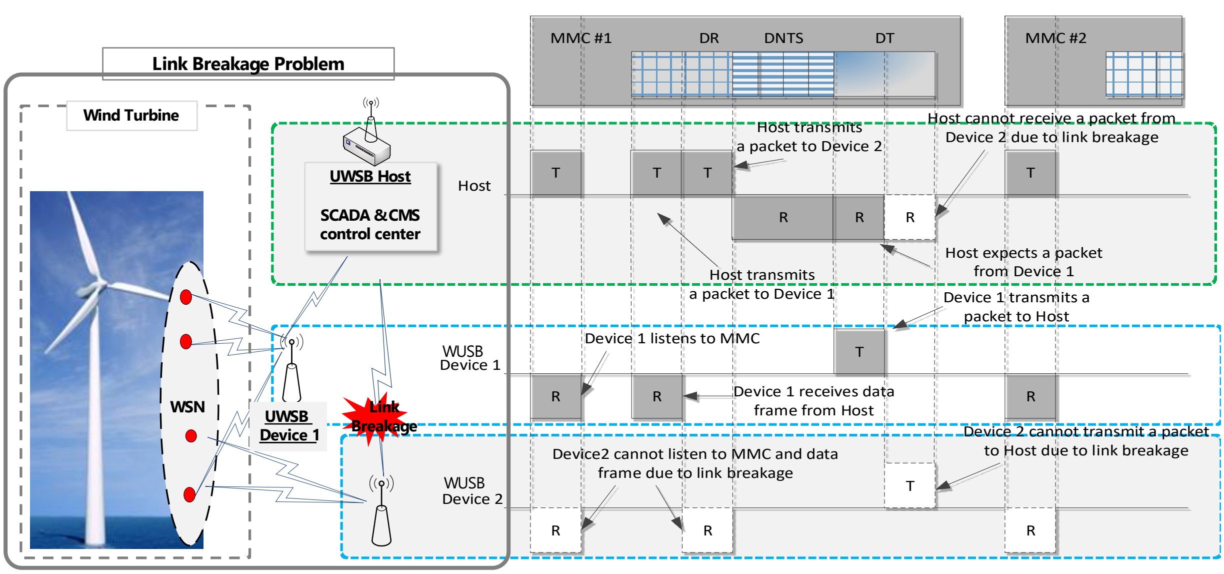

Figure 5. Illustration of link breakage problem occurred between WUSB host (SCADA & CMS) and device in WT power system with WSN-WUSB network.

When the link breakage between the WUSB host of the SCADA & CMS control center and the WT's WUSB devices in offshore occurs, the WUSB host and device cannot communicate with each other. However, if the alternative path via another WUSB device is constructed between the WUSB host and the lost WUSB device with the channel impairment, the WUSB host can communicate with the lost WUSB device as before the occurrence of the link failure. To create the alternative path, we propose new Orphan notification message protocol scheme in order to tackle down the wireless link breakage problem and thus, to improve the reliability and performance of offshore WT power monitoring system (i.e., SCADA & CMS's fault diagnosis monitoring operation) with WUSB network.

C. The Proposed Cooperative Decision Algorithm with Orphan Notification Message Protocol

The proposed cooperative decision algorithm employing Orphan Notification message protocol to provide the new path via another WUSB device to the WUSB device of concern is shown in Fig. 6. When the WUSB host transmits data frames to the target device via the helper device, it includes the requested W_{ORPHAN}CTA block in its own MMC frame as shown in Fig. 6.

- The WUSB device receiving the MMC frame including the W_{ORPHAN}CTA block checks the COM Mode (0000) bit. If the COM Mode bit is set to ORPHAN, the device begins to receive data frames from the WUSB host at *wStart* and it begins to transmit data frames received from the WUSB host at *hStart*.
- To terminate the cooperative communication, the host removes the W_{ORPHAN}CTA block in its MMC frame. The WUSB host and source device transmit data frames to the target via the helper device. In Fig. 6, the WUSB host includes the W_{ORPHAN}CTA block set the COM Mode bit to the ORPHAN in its MMC frame.
- In allocated duration, the host transmits data frames to the selected helper device. On reception of the data frame from the host, the helper device transmits the data frame to the target device in allocated duration.
- While WUSB host communicates with WUSB device, if the WUSB host does not receive the ACK of the transmitting data frame, it can recognize the channel impairment between itself and a corresponding WUSB device and transmit data frames via the helper device.
- However, if the channel impairment occurs when the WUSB device communicates with another WUSB device via the WUSB host or with the WUSB host directly, it is very difficult for the WUSB host to recognize if the link breakage occurs or not.
- If the WUSB device does not receive the ACK frame of the transmitting data frame or MMC frame transmitted by the WUSB host while a WUSB device transmits data frames to WUSB host or another WUSB device, it can recognize the channel impairment between itself and a WUSB host.
- However, it cannot inform the WUSB host that the channel impairment occurs since the WUSB protocol does not provide any link other than the link between the WUSB host and device.

Thus, we propose the Orphan Notification message to notify the WUSB host that the channel impairment occurs.

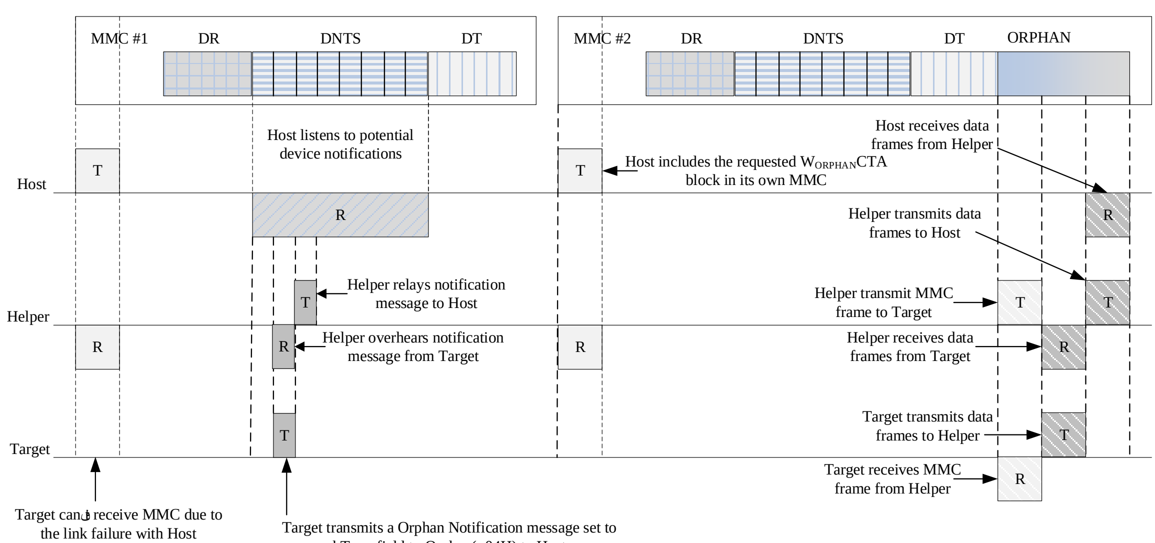

Figure 6. The example of new path configuration between WUSB host and WUSB device using the Orphan Notification message.

Since the link between the WUSB host and WUSB device suffers the channel impairment such as interference is blocked, the WUSB device needs a new path to inform the WUSB host of the channel impairment. In the WUSB standard, WUSB devices can use the DNTS duration in WUSB Transaction group to deliver the information of network management, such as connection and disconnection to the WUSB host. In the DNTS duration, the WUSB host receives only the Device Notification message from potential WUSB devices. The proposed scheme uses the DNTS duration and Device Notification message to inform the WUSB host of the channel impairment and assume that all WUSB devices were listening to the Notification message transmission.

In Fig. 6, if the target device does not MMC frame from Host, it transmits an Orphan Notification message set *bType* field to ORPHAN (=04H) to the host in DNTS duration. On reception of the Orphan Notification message from a target device, the helper device transmits the Orphan Notification message to the host in DNTS duration. When the host receives an Orphan Notification message from the helper device, it allocates the new ORPHAN duration to solve the channel impairment between the host and target. In allocated duration, the target device transmits data frames to the helper device. On reception of data frame from target device, the helper device transmits the received data frame to the host.

4. PERFORMANCE EVALUATION RESULTS

A. Simulation Parameters

All the simulations in this paper are carried out using OpenWNS [17] simulation tool. In this simulation, we compared the proposed scheme with the conventional WUSB standard [9] and the cooperative communication protocol (CCP) in the WUSB network [16]. The WUSB devices always transmitted data frames to the WUSB host in the simulations. The packet payload size transmitted by WUSB devices is 1024 bytes. The simulation parameters are given in Table 1. It is assumed in simulation that all WUSB devices are randomly distributed in a square area of 30x30m with the communication radius of 3m. The number of WUSB devices is nodes fixed at 90 and the ratio of WUSB nodes suffering link breakage condition is ranging from 10% to 80%. In this simulation, we select randomly WSUB source-target node in the WUSB network.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Network size	30 m x 30 m
Number of WUSB devices	90
Basic data rate	53.3 Mbps
Bandwidth	528 MHz
Transmission power	-10.3 dBm
Transmitter antenna gain	0 dBi
Symbol length	312.5 ns
Preamble length	9.375 μs
Header length	3.75 μs

B. Performance Evaluation Results

1) Average Packet Delivery Ratio Performance

Fig. 7 shows the average packet delivery ratio and throughput performance as a function of the ratio of WUSB device nodes suffering a severe condition in WSN-WUSB network of offshore WT power system. It should be noted that the performance of the average packet delivery ratio is very related the performance of the average data throughput. Thus, we put these two simulation results into one figure. As shown in Fig. 7, the conventional WUSB standard protocol algorithm (*Packet Delivery (Conv.WUSB)* in Fig. 7) and the CCP [16] show the lower packet delivery ratio performance than that of the proposed cooperative algorithm (*Packet Delivery (Coop.Algorithm)* in Fig. 7) based on Orphan Notification message protocol. From this result, it is concluded that the probability of wireless link breakage increases as the ratio of WUSB device nodes in the WSN-WUSB network suffering the capricious maritime climate or adverse weather condition increases. In such case, the proposed algorithm can successfully set up a new path for the relay cooperative communication link even if its link is disconnected. Even though the ratio of link disconnection increases higher, i.e., the helper device node suffers very severe transmission condition, the proposed cooperative algorithm could guarantee the almost 60% delivery success ratio compared to 30% of the conventional WUSB algorithm.

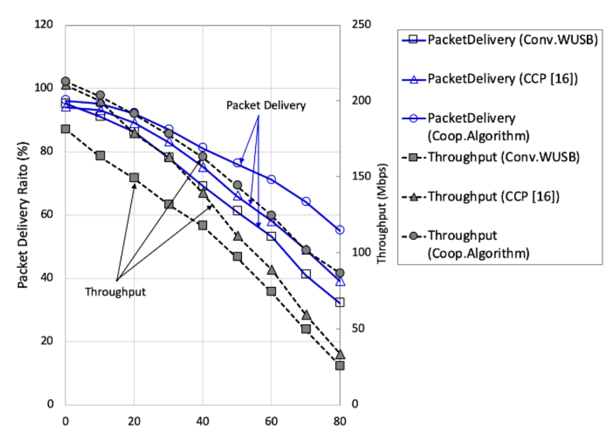

Figure 7. Average packet delivery ratio and throughput as a function of the ratio of WUSB device nodes suffering severe condition in WSN-WUSB network of WT power system.

2) Average Throughput Performance

The average throughput performance decreases for all three protocols as the ratio of mobile nodes in the WUSB network increases, as shown in Fig. 7. This is because the probability of the link failure of WUSB device with the

WUSB host increases due to the increase of mobility and offshore channel impairment. The conventional WUSB algorithm shows the biggest performance degradation, since it communicates directly with the WUSB host. On the other hand, the CCP [16] algorithm has better performance than the WUSB standard because it can transmit data through the helper node in the network environment with the low mobility. However, in a high mobility environment and under severe channel condition, the probability of disconnection with the helper node is also increases and the probability of the proposed cooperative algorithm (*Throughput (Coop.Algorithm)* in Fig. 7) to attempt on finding a new helper device also increases. The reason why the data throughput performance of both the CCP [16] algorithm and the conventional WUSB algorithm are drastically degraded is the probability of link disconnection with the WUSB host increases. On the other hand, the proposed cooperative algorithm outperforms those algorithms, since it can request and set up the relay communication link via the new helper device irrespective of highly occurred link breakage with the WUSB host.

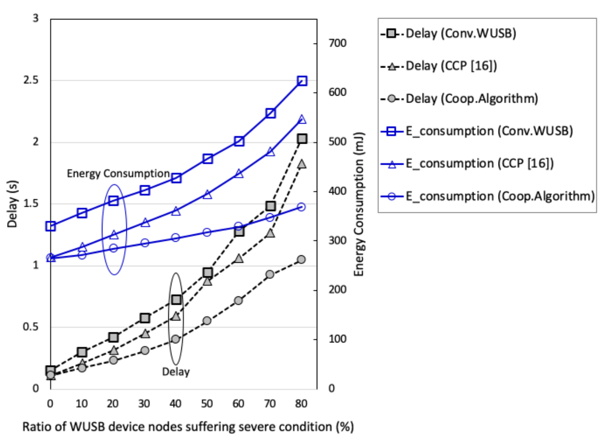

Figure 8. Average delay and energy consumption performance as a function of the ratio of WUSB device nodes suffering severe condition in WSN-WUSB network of WT power system.

3) Average Delay Performance

Fig. 8 shows the average delay and average energy consumption performance as a function of the ratio of WUSB devices nodes suffering sever channel condition. It is also noted that the performance of the average delay is very related to the performance of the average energy consumption. The increase of the delay of communication success results in the increase of energy consumption of devices. As the ratio of WUSB nodes increases, the frequency of the connection failure and recovery with WUSB host increases resulting in higher transmission delay of the data frames. Thus, the conventional WUSB algorithm without a solution of link breakage problem shows the largest latency.

As sown in Fig. 8, the CCP [16] algorithm shows lower latency than that of the conventional WUSB standard because it can transmit data frames over a better link. However, this algorithm also suffers highly occurred disconnection problem in high mobility and severe offshore condition, since under such severe condition the connection between the helper and the WUSB host is frequently disconnected. On the other hand, the proposed cooperative algorithm can find a new alternate path for both WUSB host and device even if the link breakage occurs. Therefore, the proposed algorithm shows the best performance although the average delay increases with the increase of the ratio of WUSB nodes.

4) Average Energy Consumption Performance

Fig. 8 also shows the average energy consumption performance as a function of the ratio of WUSB device nodes suffering severe condition in the WSN-WUSB network of WT power system. When the wireless link to the WUSB host is disconnected, the WUSB device turns on the RF module and monitors the channel at all intervals to receive the MMC from the WUSB host following WUSB standard protocol. Therefore, much energy consumption is inevitable when the wireless link breakage problem between WUSB host and the device occurs. It should be noted that as the ratio of WUSB device nodes suffering severe condition increases, WUSB devices are more highly likely to search all the intervals for a successful connection link. However, the proposed cooperative algorithm consumes less energy than the conventional WUSB algorithm and the CCP [16] algorithm because the helper device is more available to relay the target device's transmission.

5. CONCLUSION

In this paper, we propose a cooperative decision algorithm to enhance the reliability of the fault diagnosis monitoring of the offshore WT power system with SCADA & CMS and WSN-WUSB network. The proposed cooperative decision algorithm is useful for recovering the wireless link disconnection and providing a new link path. Based on the proposed Orphan Notification message protocol, the proposed cooperative algorithm can intelligently select the transmission path and help to maintain connectivity. Thus, the proposed algorithm can help to enhance the reliability of SCADA & CMS's fault diagnosis monitoring operation. Simulation results show the proposed algorithm outperforms in the average packet delivery ratio, data throughput, energy consumption and the average delay than the conventional WUSB standard and the CCP algorithm, even if the ratio of WUSB devices suffering severe offshore condition increases. Thus, the proposed algorithm effectively enhances the wireless link connectivity of the offshore WT power system and the overall network performance.

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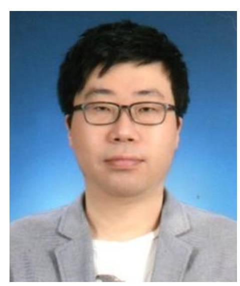

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