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An Enhanced Industrial Wireless Communication Network for Hard Real Time Performance Substation Automation Purposes

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ABSTRACT

Wireless communication network (WCN) technologies are charming solutions to bolster the conventional electrical substations with the intention of take the fashion of smart substation such as reduction in equipment, minimize the maintenance costs, flexibility, and expansion. However, the harsher challenge facing WCN employing in the electrical substation is the real time protection of substation automation system (SAS) for the high voltage devices in terms of the latency and the reliability in particular the substations of old topologies. This work suggests WCN including special types of the intermediate devices (Switched-Access Points (S-AP) and Multi Wireless Domain- Access Point (MWD-AP)) to address the expected packets congestion by creating independent wireless channels domains offering wireless channels reliability in such network topology that deals with real time data traffic (RT) and the non-real time data traffic (NRT). Riverbed modeler is adopted to simulate the model of the electrical substation network due to the rich tools of communication networks in term of industry environment. The results indicate, the suggested WCN can handle the hard real time requirements of protection from latency and data reliability points of view in case of basic capacity of 802.11a/n standards at the level of ≤ 4 msec and high data reliability.

Keywords:

Merging Unit (MU); Real time data traffic (RT); Smart substation; Substation automation system (SAS);Wireless communication network (WCN).

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1. INTRODUCTION

The main pillar of any smart substation is a robust communication network that could hold the requirements of SAS. WCN technologies offer significant attributes like flexibility and low-cost maintenance. Unfortunately, the unguided channel suffers from substantial problems comparing to guided channel in term of industrial environment such as the effect of electro-magnetic interference (EMI)) and the effected packets collisions in a shared channel [1], [2] , [3]. Moreover, the real time protection is a crucial and difficult point to achieve based on latency issues of wireless impairments [4]. Some of related works such as [5], [6], [7] paid the intention to address the previous issues by assuming the substation is a modern building dealing with three wireless devices only to model a bay of the electrical substation based on IEC 61850 protocol. In fact, lots of substations are an old infrastructures and deal with different topologies and protocols. However, the suggested solutions by the previous works assume simple substation architecture. Whilst, SAS of the most substations comprises more than one protocol for communication and have different topologies to create the bay of transformer or feeder comparing to modern design of substations.

The problem statement of such environment is how to handle the availability of wireless channel or wireless channel reliability. In other words, many wireless stations may compete to access one wireless channel, i.e., one collision domain for many stations produces retransmission in the wireless channel. The obtained result of such case leads to more elapsed time with respect to latency. This problem calls a novel scheme to compensate the impairments of the limited wireless channel in contrast to wired channel.

The main contribution of this research is addressing the hard real time protection (below 4 msec) for SAS, it is a great challenge to handle for older electrical substation topologies that are still under operation. This work offers Switched-access point (S-AP) and multi-wireless domains-access point (MWD-AP) in order to achieve hard real time protection for power system in the wireless environment, heavy data traffic (real time and non-real time data traffic), and industrial environment. This scheme of wireless intermediate devices contributes in providing significant advantages to (1) offer the suitable capacity for substation automation in terms of wireless channel reliability, (2) scalability, and (3) hard real time protection based on the basic capacity of 802.11 wireless standards without any enhancement tools to support the capacity of wireless technologies. To our best knowledge, there are no previous related works cover this essential point.

1.1. Related works

This subsection discusses the recent related works that interest in employing the wireless communication techniques for the electrical substation applications.

In [8], the authors discussed and tested the feasibility of wireless communication based on 802.11ah for intelligent substation. Hence, the feature of 802.11ah standard is the low power consumption. The adopted network included one AP and six wireless stations. They dealt with the metrics of signal to noise ratio. However, to handle the main applications of the substation, it is expected to deal with more than 6 stations. In addition, the work in [8] does not include any calculation or estimation to the latency to prove the suitability of 802.11ah to the applications requirements of substation particular the application of power system protection.

Design a secondary equipment-oriented error prevention system (SSE-Oriented Error) using wireless communication technology in intelligent substation is adopted by [9]. The authors chose 802,11ac wireless standard to build SSE for prevention, control, and management. Anyway, the work in [9] develops one part of substation toward the wireless techniques. Furthermore, 802.11ac could provide high data rate but it consumes more power and suffers from the multiple wireless devices in term of interference.

The authors in [10] paid attention to Zigbee technology in order to design a wireless communication for substation. The main benefit of Zigbee is to mitigate the strong EMI and RFI prevailing in the substation arena. The intensive work adopted Zigbee technology to send the information of phasor measurements units to the control room inside one substation for monitoring purposes. However, the substation contains various activities and it is not limited to the monitoring application. Further, Zigbee technique suffers from the low data rate and it is hard to such technology alone to compensate the heavy data rate of substation data traffic.

N. Kumari in [11] offered a study including a comparison among three different wireless communication technologies (802.11g, 4 generation (4G), and 5G) to serve the substation. The author presented a simple model including a sender transmits sampled values to a receiver to simulate a simple status of electrical substation. The results of the work indicated that the technology of 5G submitted lowest latency. Nevertheless, the model of the electrical substation is more complex than the offered scenario and the cost of employing the technology of 5G is high compared to the technology of WLAN as well as the employing of 5G technology requires third parity for operation.

Some of works discussed the capabilities of address wireless sensor network (WSN) for the applications of substation [12] [13] [14]. Unfortunately, WSN is basically offering low data rate therefore this type of technology faces hard difficulties from the heavy data traffic point of view.

On the other hand, the works in [15] [7] [6] represented the closest research trend this work. Hence, they presented 802.11 standards (802.11b, 802.11g, 802.11a, and 802.11n) to employ wireless communication for the modern communication protocol only of SAS in terms of monitoring and protection.

The current work designs wireless communication network in terms of real time data and non-real time data for the conventional electrical substation to take the advantages of low-cost initialization and maintenance, flexibility, and expansion. That is, handling the applications of substation automation in terms of monitoring and protection to develop the traditional substation toward smart substation. Further, this work aims to meet the requirements of SAS in terms of latency and data reliability based on the well-known protocol stack transmission control protocol/internet protocol (TCP/IP) and traditional topology of substation elements.

2. REAL TIME PROTECTION CHALLENGE OF SAS IN WIRELESS ENVIRONMENT

The real time protection is a priorate function of SAS to protect the valuable intelligent electronic devices (IEDs) of power system against different types of faults (like overcurrent fault) [16]. The real time protection latency can be defined as an elapsed time from generating the sampled values until implemented the suitable actions to protect the components of electrical substations. According to [17], the latency from sensing the fault occurrence to circuit breaker action should be less than 4m sec for transmission substation and 10 msec for distribution substation to keep the hardware components under robust conditions in term of protection. The overall latency of real time protection includes two periods. The first period handles the latency from producing sampled values (fault indication) at merging unit to the control and protection intelligent electronic device (C&P IED). Whilst, the second period comprises the time of making a decision at C&P IED as a trip message in addition to sending this message (trip) to the circuit breaker IED to implement the action of separation the faulted zone. In robust conditions, the latency of trip message should be not exceeded 4 msec [18]. The challenge of latency is solved using wired technologies [4] [17] but the wireless technologies need to address other solutions to make such technologies are suitable for SAS requirements.

According to 802.11 standard [19], the process of transmission depends on time division duplex (TTD). Therefore one transmission only can happen at a time. In the case of more than one transmission, the collision among the different transmissions may occur. The method of solving the collisions in 802.11 is carrier cense multiple access/ collision avoidance (CSMA/CA). In this algorithm, the node firstly listens to the channel if the channel is idle, the node sends the data after predetermined time. In the case of busy channel, the node has to defer its transmission after nominal period based on the exponential backoff algorithm. Obviously, such environment is sensitive to the number of nodes and the size of data traffic in particular the real time protection from latency point of view.

However, the calculation of latency in wireless medium depends on different factors such the data rate base-standard and the distance between sender and receiver. But the major one is the WLAN delay that includes the mechanism of sending the messages of request to send (RTS), clear to send (CTS), and waiting many types of periods such distribution interframe space (DIFS) and short interframe space (SIFS), in addition to the delay of data itself and the acknowledgement messages to notify the sender with successful receiving of data [20]. Other factors such as the hardware capability of wireless node contribute in calculation of the latency [21]. The WLAN delay is a significant because it depends on WCN and it influences by network status (i.e., any congestion in the wireless network can lead to increase WLAN delay to high magnitude).

3. THE SUGGESTED WCN INFRASTRUCTURE FOR SAS

The main undermined to the capacity of wireless network is the common collision domain in a shared channel. Therefore, such environment at heavy data traffic and multi-wireless devices compete to access the wireless channel, causes congestion produced larger latency. As a consequent, WCN fails to handle the requirements of real time protection.

In the electrical substation, the design of communication network should include a subnet for each bay (transformer or feeder). Then each subnet of bays connects to the subnet of surveillance room (SR). Such structure of WCN has two bottlenecks may cause congestion. In each subnet of the bays, the AP will represent bottleneck because each data is sent inside the subnet should pass via AP. The second is the joint between subnets of bay with the subnet of SR.

This work suggests WCN could break or mitigate the data traffic congestions at each bottleneck in this cyber-structure via two types of wireless intermediate devices, one for each bay subnet or called Switched- access point (S-AP) and another one for SR subnet called multi wireless domain access point (MWD-AP).

3.1. Switched-AP

The Switched-AP is a modified AP consists of multi-identical full functionality-AP connecting together by very fast switching fabric. Each sub-AP contains processor, memory, interconnection network, wired network interface card (NIC) to connect sub-AP to switching fabric by high-speed bus, and wireless network interface card (WNIC) to provide the wireless coverage area and the interface with the wireless network. The aim of this design is creating reliable channel communication in each subnet by creating multi wireless capacity domains in suitable method to handle the hard requirements of protection as a term of latency.

Fig. 1 explains the role of Switched-AP (S-AP) as compared to the traditional-AP (T-AP) inside the subnet of each bay. T-AP has one wireless channel domain to initiate the connections with multiple nodes, this style causes long latency in case of SAS to cover all IEDs in the same subnet.

In contrast, S-AP creates multi-independent wireless domains (multi basic service set (BSSs)). The BSS of each sub-AP is allocated in suitable way to cover specific IED devices in order to distribute the data traffic in each wireless channel domain in balance as possible to compensate any expected congestion. This method initiates multi wireless connections between S-AP and multiple IEDs at same time in elegance fashion henceforth each connection has separated wireless channel under unique BSS. Thereby, the wireless channel reliability is achieved by disassemble the one collision domain into multi-domains besides offers the capability of distributing the data traffic to multi-hardware parts each one provides complete processing based full capacity of the wireless standard. It is worth to mention, each sub-AP in S-AP can process the data independently of other units of sub-AP to provide the capability of compensate the heavy data traffic.

In summary, the physical structure of S-AP provides many advantages to match the nature of the SAS applications like the ability of process heavy traffic, compensate the wireless collisions, dealing with multiple IEDs independently, and increasing the wireless capacity.

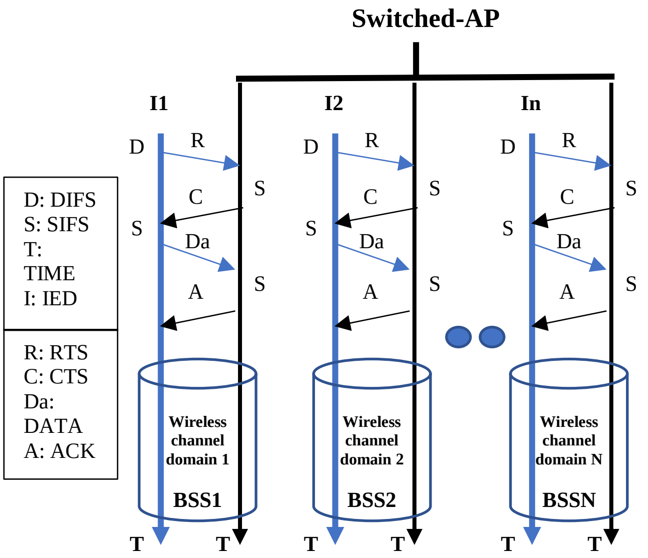

Fig. 1 Switched-AP in case of creating connections with multiple IEDs at same time.

3.2 Multi-wireless domain access point (MWD-AP)

In the electrical substations, each subnet of bays has two types of data traffic. The first is generated and processed inside the subnet itself to protect the power system in term of automation. Whilst, the second data traffic transfers from/to each subnet to /from SR subnet. However, such AP represents bottleneck to the whole network of SAS. In the case of heavy traffic, the congestion is expected at a T-AP. For instance, each bay subnet sends data traffic from each C&P IED to the global controller in SR subnet. The whole traffic will pass via such AP. The gathering data at one wireless channel (one wireless bridge) lead to effected collision domain producing lost packets.

This research submits MWD-AP to address the issue of congestion at SR subnet to enhance the wireless channel availability. MWD-AP is AP lies in SR subnet and it has wireless interfaces matching the number of bays subnets plus SR subnet as shown in Fig. 2. The wireless interface is modelled by wireless network interface card (WINC) and each one has unique BSS; it deals with physical layer and data link layer then is connected to the network layer at AP itself. This design solves the problem of one collision domain by creating multi wireless domains that contribute in providing more reliability in term of communication besides compensate the process time of higher layers in one intermediate device.

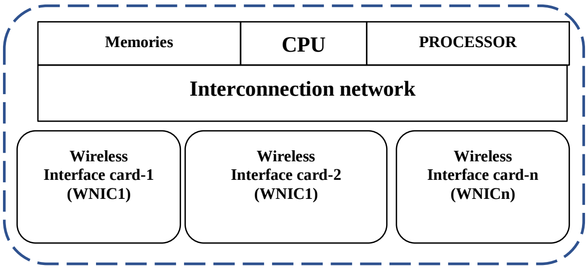

Fig. 2 The components of MWD-AP.

As a result, the design of WCN can handle smoothed data traffic transferring for SAS to compensate the requirements of real time protection. In addition, such design increases the reliability of communication by creation separated wireless channels in each subnet of bays and between each subnet of bays and the subnet of SR.

4. MODEL DESCRIPTION

This work adopts the layout of conventional distribution substation (33kv/11kv) as a typical case. This is related to explain the capability of developing the traditional electrical substation with conventional components from wired communication network into wireless communication network in order to upgrade the traditional substation to the level of smart substation. Fig. 3 explains the diagram of distribution substation, the designed wireless network includes eight subnets: one subnet for transformer bay_1, one subnet for transformer bay_2, five subnets for feeders (each feeder is represented by one subnet), and subnet for SR as shown in Fig. 4.

Each subnet is an identical. It is modelled by different types of IEDs representing eight signals' sources (SSs) or one merging unit (MU) to generate the signals of measuring, three actuators (AC) for the protection, and one local controller (LC) for automation decisions. Whilst, the SR subnet consists of one global controller (GC) and human machine interface (HMI) for Monitoring, administration, interfaces and control [17].

Table 1 explains the processing rate of IEDs components of the substation [22]. Table 2 lists the data traffic descriptions of the electrical substation. The data of electrical substation addresses two branches of traffic: real time traffic and non-real time traffic. This work holds the two types of data traffic to simulate the realistic state of substation data traffic.

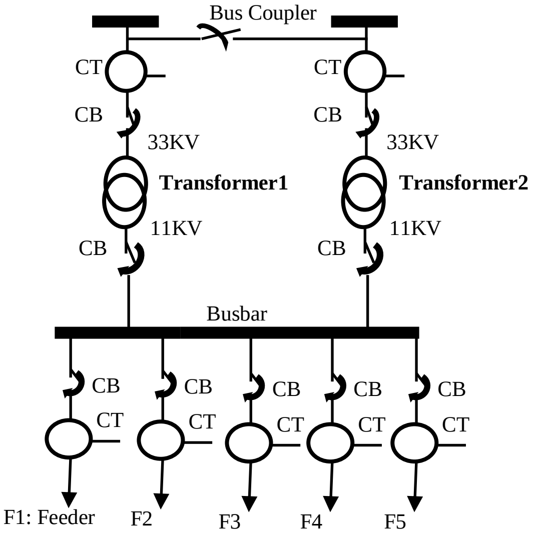

Fig. 3 The diagram of distribution substation.

Riverbed modeler is exploited to build wireless communication network for MUS where each sub network (subnet) is wirelessly covered by access point. The work deals with three types of wireless local area network standards: 802.11g, 802.11a, and 802.11n. It is worth mentioning, the effect of industrial environment in term of noise is taken under consideration. Based on practical measurements of [5], it is added additional amount of noise to our model to simulate harsh industrial environment.

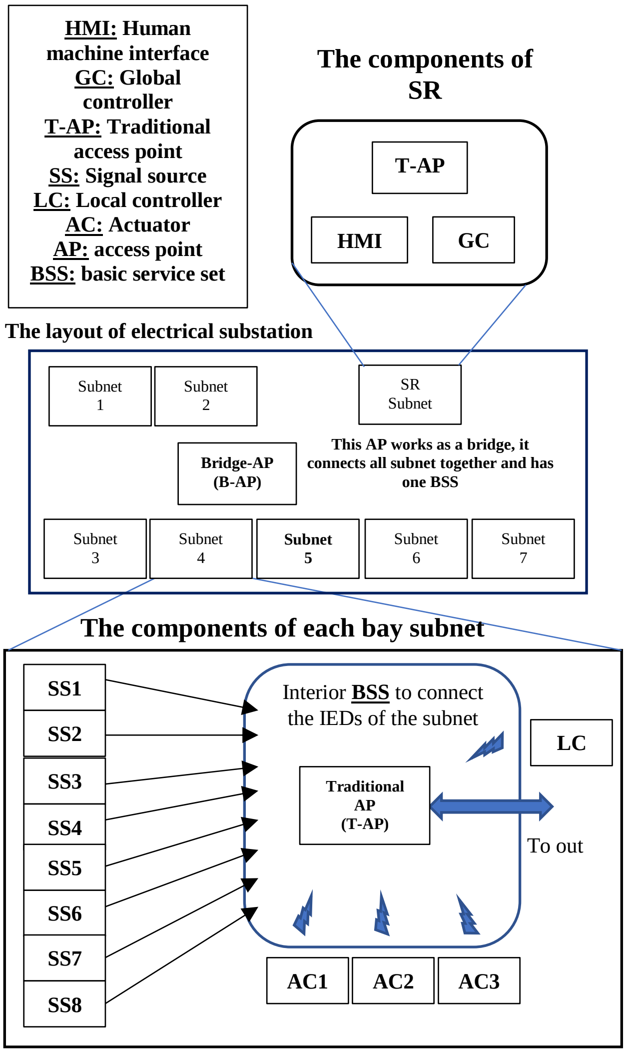

Fig. 4 The components and layout of T_WCN.

Table 1: Processing rate of IEDs components in the substation [22].

IED type	Processing rate (Packet/sec)
The sources of signals protection	5000
Merging unit	30000
Actuator	10000
Local controller device	20000
Global controller device	60000

Table 2: The pattern of substation traffic [4] [17].

<table>
<tr><th colspan="5">The scenario of traditional WCN</th></tr>
<tr><th>Source</th><th>Destination</th><th>Packet length (byte)</th><th>Packet rate (Packet/sec)</th><th>Protocol</th></tr>
<tr><td rowspan="2">SS1, SS2, and SS3</td><td>LC, AC1, AC2, and GC</td><td>32</td><td>1000</td><td>UDP</td></tr>
<tr><td>LC, AC1, and AC2</td><td>32</td><td>10</td><td>UDP</td></tr>
<tr><td>SS4, SS5, SS6, SS7, and SS8</td><td>LC, AC1, and AC2</td><td>32</td><td>10</td><td>UDP</td></tr>
<tr><td rowspan="3">LC and GC</td><td>AC3</td><td>16</td><td>250</td><td>UDP</td></tr>
<tr><td>AC3</td><td>16</td><td>1</td><td>UDP</td></tr>
<tr><td>HMI</td><td>1M</td><td>2 Files/sec</td><td>TCP</td></tr>
<tr><td>HMI</td><td>S1, S2, S3, LC and GC</td><td>1M</td><td>1</td><td>TCP</td></tr>
<tr><th colspan="5">The scenario of employing Merging unit (MU)</th></tr>
<tr><td rowspan="4">MU</td><td>LC</td><td>32</td><td rowspan="4">Depending on the scenario: 400, 800,1600 or 4000 sample/sec</td><td>UDP</td></tr>
<tr><td>AC1</td><td>32</td><td>UDP</td></tr>
<tr><td>AC2</td><td>32</td><td>UDP</td></tr>
<tr><td>GC</td><td>32</td><td>UDP</td></tr>
<tr><td>LC and GC</td><td colspan="4">As same the scenario of traditional WCN.</td></tr>
<tr><td>HMI</td><td colspan="4">As same the scenario of traditional WCN.</td></tr>
</table>

4.1 Scenarios of simulation

First Scenario: Traditional Wireless Communication Network (T_WCN)

In this scenario, T-AP has two BSSs (one to provide the wireless coverage area for the subnet itself. While the second is used to connect the subnet with another AP in the core of WCN (i.e., Bridge-AP) that exploited to connect all bay subnets to SR subnet. In addition, the subnet of SR is covered by traditional AP such the AP at each bay subnet. This scenario simulates the traditional status of conventional substation.

Second Scenario: Employing Merging Units in Wireless Communication Network (MU_WCN)

In this scenario there is one modification comparing to the first scenario: In each subnet of bays: employing MU that represents an IED device can gather the eight signals' sources in the inputs of one IED device to produce them from one output at different rate of sampling frequency such 400, 800, 1600, and 400 (sample/sec) [23] [5]. The target of this scenario is to compensate the multiple sources of signals with one device to reduce the competition on the wireless channel.

Third Scenario: Switched-AP in Wireless Communication Network (S_WCN)

As compared to previous scenario, it cancels Bridge-AP from the core of WCN and replacing T-AP at SR subnet with MWD-AP to mitigate the congestion of data traffic at the core of WCN, and replacing the T-AP at each subnet of bay with S-AP to provide the suitable wireless channel availability to handle the heavy data traffic at each bay subnet.

5. RESULTS AND DISCUSSIONS

The behavior of 802.11g standard in term of T-WCN is explained in Fig. 5. This Fig. interprets two cases of the traffic patterns with the simulation time equal to 1800 sec in terms of generated traffic, throughput, and lost packets. This first case represents the traffic of real time traffic only (RT) while the second case deals with RT plus non-real time traffic (file transfer protocol traffic (FTP)).

It is clear that, 802.11g standard fails in handling the traffic of SAS in the case of RT only and the case of FTP+RT. In case of adding the traffic of FTP to the WCN, the system is completely fails and the data is going to drop due to the interferences, limited capacity and the heavy data traffic. The results indicate that, most of the generated packets in the two cases are lost before reaching to the destinations. For instance, the lost packets in the cases of RT only and FTP+RT are up to 24k and 28k (packets/sec) respectively while the generated packets are 26k and 31k (packets/sec) respectively. It noted that, the throughput at the steady state phase is 2k and 2.2k (packets/sec) for the cases RT only and FTP+RT respectively.

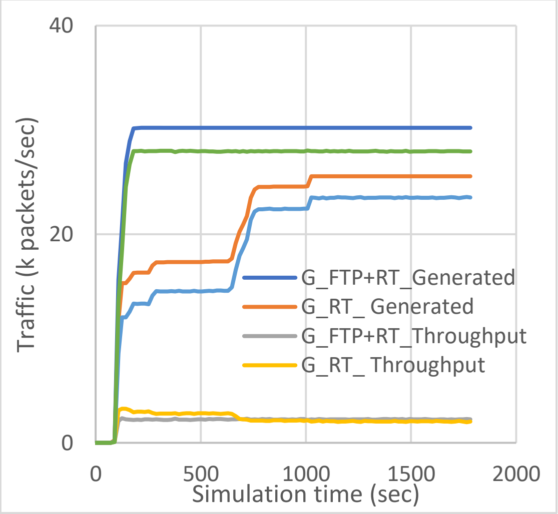

Fig. 5 The traffic of T_WCN without and with FTP in case of 802.11g.

Fig. 6 illustrates a comparison in terms of latency and packet loss between T-WCN and MU-WCN to explain the impact of MUs in WCN with 802.11a standard. MU can produce sample/sec in different fashion such 400, 800, 1600, and 4000. However, 4000 sample/sec represents heavy data traffic style but it reflects quite accurate level of data for power system while the case of 400 sample/sec is light data traffic with less accurate data.

The metric of packet loss represents the lost packet in the channel, it collects after subtract the received packets from transmit packets. This metric offers sense about the received packet's reliability, when the magnitude of the metric is high meaning less received packet's reliability [16].

In addition, the average latency in case of MU-WCN is less than the case of T-WCN because MU-WCN can decrease the packet loss of RT data traffic comparing to the case of T-WCN. For instance, in the worst case of MU-WCN (MU=4000) with respect to packet loss, the WCN saves about 30250 packets from the lost as compared to T-WCN. That is, T-WCN faces difficult to handle RT data traffic and the non-real time traffic because the congestion of heavy real time traffic at APs prevents the non-real time traffic from reaching the destinations due to the priority of passing to real time traffic. However, the results explain that the latency of all cases is not appropriate for substation protection.

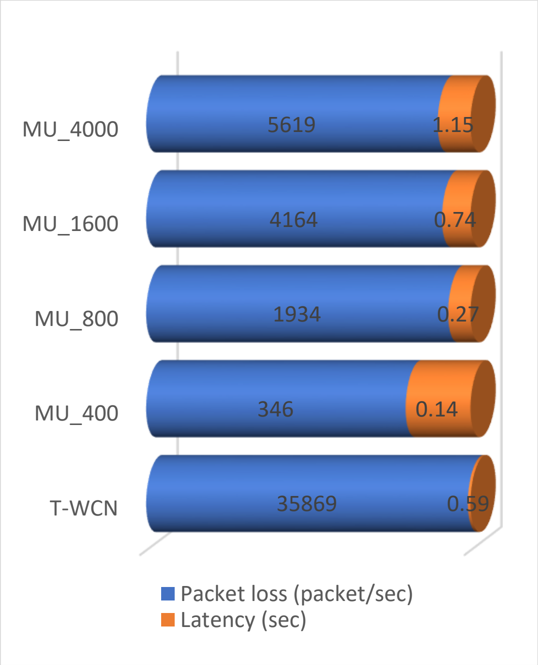

Fig. 6 Latency and packet loss of T_WCN and MU_WCN.

Table 3 compares among the local and global real time protection latency, RT packet loss, RT packet received reliability of MU-WCN, and S-WCN in case of 802.11a standard with MU=800 and MU=1600, to explain the advantages of S-WCN and its ability to handle the requirements of hard real time protection.

Packet received reliability in term of RT data traffic represents the percentage ratio of received traffic over sent traffic [24], this metric and local real time protection latency together explains the ability of the SAS to handle the requirements of real time protection. However, the required local real time latency for protection should be less than 4 msec [17] and packet received reliability should be larger than 90% in the wireless environment [16] in order to serve the electrical substation successfully by SAS. Furthermore, S-WCN can provide suitable environment for SAS in terms of the latency and the packet received reliability while MU-WCN cannot handle these conditions. Referring to MU=1600, S-WCN is still submitting behavior better than MU-WCN from latency, packet loss, and the reliability points of view but at sampling rate of MU = 1600, S-WCN fails in handle the requirements of real time protection because the real time latency exceeds the limit of 4 msec largely. In summary, S-WCN can address the suitable environment with 802.11a for SAS at sampling rate of MUs less than or equal to 800 sample/sec.

Table 3: Local and global real time protection in case of MU=800 and 1600 sample/sec.

802.11a 5GHz, merging unit (MU) produces 800 (Sampling/sec) in each bay subnet				
Scenario/ Sampling	**A:** Latency from MU to local controller		**B:** Latency from Local Controller to actuator	
	Average (m sec)	Max (m sec)	Average (m sec)	Max (m sec)
MU-WCN MU=800	167.7	186.9	314.5	321.1
S-WCN MU=800	1.09	1.74	0.66	0.74
MU-WCN MU=1600	757.2	1082.2	0.36	0.41
S-WCN MU=1600	1.53	2.37	254.6	312.3
	C= A+B Local RT protection per subnet			
	Average (m sec)		Max (m sec)	
MU-WCN MU=800	482.2		508	
S-WCN MU=800	**1.75**		**2.48**	
MU-WCN MU=1600	757.56		1082.61	

S-WCN MU=1600	256.13		314.67	
	D: Latency from global controller to local controller		E= D+B Global real time protection	
	Average (m sec)	Max (m sec)	Average (m sec)	Max (m sec)
MU-WCN MU=800	320.1	331.2	634.6	652.3
S-WCN MU=800	271.3	287.9	271.96	288.64
MU-WCN MU=1600	773	883.3	773.36	883.71
S-WCN MU=1600	288.9	309.6	543.5	621.9
	RT Packet loss (packet/sec)		**RT Packet received reliability (%)**	
MU-WCN MU=800	**1934**		**51**	
S-WCN MU=800	**129**		**97**	
MU-WCN MU=1600	4164		15	
S-WCN MU=1600	631		90	

Table 4 demonstrates the performance of 802.11n standard in terms of local and global real time protection, packet loss, and packet received reliability at sampling rate of MU = 1600 and 4000 sample/sec.

Table 4: Local and global real time protection in case of 802.11n.

802.11n 5GHz				
Scenario/ Sampling	A: Latency from MU to local controller		B: Latency from Local Controller to actuator	
	Average (m sec)	Max (m sec)	Average (m sec)	Max (m sec)
MU-WCN MU=1600	4.11	7.52	7.44	8.51
S-WCN MU=1600	1.31	2	0.66	0.75
MU-WCN MU=4000	11.14	17.84	11.26	13.07
S-WCN MU=4000	1.28	1.68	0.95	1.08
	C= A+B Local RT protection per subnet			
	Average (m sec)		Max (m sec)	
MU-WCN MU=1600	11.56		16.04	
S-WCN MU=1600	**1.98**		**2.75**	
MU-WCN MU=4000	22.4		30.91	
S-WCN MU=4000	**2.23**		**2.76**	
	D: Latency from global controller to local controller		E= D+B Global real time protection	
	Average (m sec)	Max (m sec)	Average (m sec)	Max (m sec)
MU-WCN MU=1600	9.92	11.25	17.36	19.77
S-WCN MU=1600	3.11	3.9	3.78	4.66
MU-WCN MU=4000	13.53	17.54	24.81	30.61
S-WCN MU=4000	3.85	5.23	4.8	6.32
	RT Packet loss (packet/sec)		**RT Packet received reliability (%)**	
MU-WCN MU=1600	79		97	
S-WCN MU=1600	**14**		**99**	
MU-WCN MU=4000	292		94	
S-WCN MU=4000	**15**		**99**	

Obviously, 802.11n standard offers latency and packet received reliability performances better than 802.11a standard due to the larger capacity of standard (65Mbps) comparing to 802.11a (54Mbps) besides the ability to block the messages of acknowledgement to take the advantage of shorter latency. Furthermore, S-WCN submits perfect performance from latency and packet received reliability points of view comparing to MU-WCN in case of MU=1600 sample/sec and MU=4000 sample/sec.

Finally, Table 5 explains the differences among this work and closest related works. However, it is important to indicate some points to discuss. Firstly, the mentioned previous works dealt with modelling each subnet of bay by three IEDs (MU, protection and control, and circuit breaker) based on modern design of electrical substation. However, what will happen if each bay needs to more than three devices to model the communication networks specially with significant number of oldest designs of electrical substation topologies that are still under operation. For instance, the access to wireless channel requires competition among wireless devices. Therefore, if one device only is added to the model of bay communication network based on IEC 61850 communication protocol leading to 25% increment in competition to access the channel in the severed environment that is very sensitive to the delay. Another sticking point, MU in the previous works is modelled using three-layer stack model to compensate the latency. But IED protection and control, and circuit breaker are modelled using five-layer stack according to IEC 61850. Nevertheless, three-layer stack model can deprive MU from many advantages comparing to five-layer stack therefore MU based-three layers cannot recognize the different types of traffic based-transport layer in addition to causing regulation issues related to manufacturing and matching among different vendors. Moreover, the magnitude of non-real time data traffic may reach to effected value. As a consequent, this value effects deeply on the requirements of real time data traffic hence this factor does not take in account in the previous works in particular in case of large values of non-real time traffic in the whole communication network of electrical substation.

Table 5: Comparison among this work and some previous related works.

Issue	[15]	[7]	[23]	[6]	[25]	**This work**
Hard real time protection (below 4m sec) under basic capability of wireless standards	NO	NO	NO	NO	NO	YES
WLAN standards	b, g, and a	a & n	n	n	b &g	g, a, & n
Wireless channel availability	NO	NO	NO	NO	NO	YES
IEDs Processing capability effect	NO	NO	NO	NO	NO	YES
Effect of non-real time traffic on real time traffic in case of intermediate devices existence	NO	NO	NO	NO	NO	YES
AP scheme	Traditional AP(T-AP)	T-AP	T-AP	T-AP	T-AP	Novel scheme of AP
Method	OPNET	OPNET	OPNET	OPNET	OPNET	OPNET
Number of IEDs per subnet (3 or more)	3	3	3	3	NO	≥5
Number of layers (Stack model) of IEDs (3 or 5 layers)	3 (MU),5(rest IEDs)	3 (MU),5(rest IEDs)	3 (MU),5(rest IEDs)	3 (MU),5(rest IEDs)	3 (MU),5(rest IEDs)	Uniform for all IEDs (5 only)
Metrics: latency(L), packet loss (PL), reliability (R), processing capability (PC), and traffic(T)	L,T	L,T	L,T	L,T	L,T	L,PL,R,PC,T

6. CONCLUSIONS

This research suggested WCN and created two types of wireless intermediate devices (S-AP and MWD-AP) to address the requirements of SAS in smart electrical substation from protection point of view.

The results indicated, T-WCN does not hold the required conditions of SAS with any type of WLAN standards (g, a, and n) in case of traditional topologies of electrical substations. In contrast, S-WCN successes to solve the impairments of wireless channel and limited capacity of WLAN standards by employing the concept of MUs to compensate the multiple wireless signal sources. In addition, the proposed WCN exploits the new scheme of wireless intermediate devices (S-AP and MWD-AP) to contained the processing of heavy data traffic besides providing the wireless channel availability (wireless channel reliability). In 802.11a, the suggested network offered an advantage comparing to MU-WCN by reducing the local real time protection latency and increasing the received packet reliability to more than 97%. As a consequent, S-WCN relieved 802.11a to handle the requirements of SAS at MUs produce 800 sample/sec or least. On the other hand, 802.11n wireless standard submitted better performance than 802.11a standard due to larger capacity comparing to 802.11a. The impact of S-WCN pushed 802.11n standard to handle the requirements of SAS at MUs produce 1600 sample/sec and 4000 sample/sec.

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شبكة اتصالات لاسلكية صناعية محسنة لاغراض اتمتة المحطات الفرعية ذات الاداء الحاد في الزمن الحقيقي

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الملخص

تعد تقنيات شبكة الاتصالات اللاسلكية حلولًا جذابة لترقية المحطات الكهربائية الفرعية التقليدية الى المحطات الفرعية الذكية ذات ميزات مثل تقليل المعدات وتقليل تكاليف الصيانة والمرونة والتوسع. ومع ذلك، فإن التحدي الأصعب الذي يواجه شبكات الاتصالات اللاسلكية في المحطة الفرعية الكهربائية هو حماية اجهزة الجهد العالي في الوقت الفعلي في نظام أتمتة المحطات الفرعية من حيث زمن الوصول والموثوقية للبيانات وعلى وجه الخصوص المحطات الفرعية للطوبولوجيات القديمة. يقترح هذا العمل شبكة اتصالات لاسلكية تتضمن أنواع خاصة من الأجهزة الوسيطة (نقاط الوصول المبدلة) ونقطة الوصول (متعددة النطاقات اللاسلكية) لمعالجة الازدحام المتوقع للحزم من خلال إنشاء نطاقات قنوات لاسلكية مستقلة توفر موثوقية للقنوات اللاسلكية. تم اعتماد برنامج الريفربد لمحاكاة نموذج شبكة المحطات الفرعية الكهربائية بسبب الأدوات الغنية لشبكات الاتصال من حيث البيئة الصناعية. تشير النتائج إلى أن شبكة الاتصالات اللاسلكية المقترحة يمكن أن تتعامل مع متطلبات الوقت الحقيقي الصعب للحماية من ناحية زمن الوصول و الموثوقة للبيانات في حالة القدرة الأساسية للمعايير اللاسلكية a/n على مستوى اقل او يساوي 4 ملي ثانية وموثوقيةعالية للبيانات.

الكلمات الداله:

وحدة المزج، بيانات الزمن الحقيقي، محطة فرعية ذكية، نظام اتمتة المحطات الفرعية، شبكة اتصالات لاسلكية.