A Comprehensive Investigation of Wireless LAN for IEC 61850–Based Smart Distribution Substation Applications

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***Abstract*—Today's power grid is facing many challenges due to increasing load growth, aging of existing power infrastructures, high penetration of renewable, and lack of fast monitoring and control. Utilizing recent developments in Information and Communication Technologies (ICT) at the power-distribution level, various smart-grid applications can be realized to achieve reliable, efficient, and green power. Interoperable exchange of information is already standardized in the globally accepted smart-grid standard, IEC 61850, over the local area networks (LANs). Due to low installation cost, sufficient data rates, and ease of deployment, the industrial wireless LAN technologies are gaining interest among power utilities, especially for less critical smart distribution network applications. Extensive work is carried out to examine the wireless LAN (WLAN) technology within a power distribution substation. The first phase of the work is initiated with the radio noise interference measurements at 27.6- and 13.8-kV distribution substations, including circuit breaker switching operations. For a detailed investigation, the hardware prototypes of WLAN-enabled IEC 61850 devices are developed using industrial embedded systems, and the performance of smart distribution substation monitoring, control, and protection applications is analyzed for various scenarios using a round trip-time of IEC 61850 application messages. Finally, to examine the real-world field performance, the developed prototype devices are installed in the switchyard and control room of 27.6 power distribution substation, and testing results of various applications are discussed.**

***Index Terms*—Distribution substation automation, IEC 61850, IEEE 802.11, intelligent electronics devices (IEDs), smart grid.**

I. INTRODUCTION

SMART distribution systems are crucial for realizing an envisioned smart grid, especially in challenging times with high penetration of renewable energy resources, plug-in hybrid vehicles, over power distribution equipment and networks that are many decades old [1]. Therefore, the implementation of Information and Communication Technology (ICT) in distribution substations is important to achieve intelligent control, monitoring, and protection applications. The IEC 61850 [2] is already accepted in smart-grid framework worldwide for common information exchange among intelligent electronic devices (IEDs) within power substations [3]. The IEC 61850 standard proposes Ethernet local area network (LAN) to integrate substation automation devices supplied by different manufactures. References [4]–[6] provide assessment of IEC 61850 communication using wired Ethernet LAN. The wireless Ethernet LAN (presently standardized in IEEE 802.11) has already been included in a smart-grid roadmap of the National Institute of Standards and Technology (NIST) [3], and recent studies have demonstrated the suitability of wireless LAN (WLAN) technologies for industrial environments as an extension of industrial Ethernet for various industrial applications [7], [8]. Moreover, wireless technologies are more promising to realize smart distribution substation applications, especially due to less stringent performance requirements and limited availability of infrastructure investments at the power-distribution level [9]–[11]. Moreover, the international institutes have also presented the potential of these technologies for future substation protection, control, and monitoring-related applications [12]–[15]. Product developers for power utilities have initiated developing robust WLAN substation automation devices [16], [17]. Although some works on wireless applications for substations have been demonstrated [18]–[20], there is no any thorough investigation available in the literatures to examine the performance of WLANs for the time-delay requirement criteria specified in IEC 61850 part 5.

This paper presents an assessment of WLAN performance for IEC 61850–based smart distribution substation applications. The work starts by identifying the potential smart distribution substation applications, for which WLAN technology can be more suitable technically as well as economically (Section III). Then, the noise-level measurements are carried out at various 27.6- and 13.8-kV distribution substations using the commercial spectrum and network analyzers (Section IV). The next stage of this work includes the laboratory prototype development of wireless enabled IEC 61850–based substation devices, such as wireless IEDs and a merging unit (MU) playback, using an industrial embedded system with a hard real-time platform. In order to assess WLAN performance, the further laboratory setup includes commercial wireless access point (AP), traffic generator, noise sources, network analyzer, and spectrum analyzer. The examination results from the developed hardware laboratory are discussed in detail (Section V). Finally, to analyze the performance of WLAN-based communication networks for various smart-grid applications in the substation, the field testing of WLAN-enabled IEC 61850 networks for various control and

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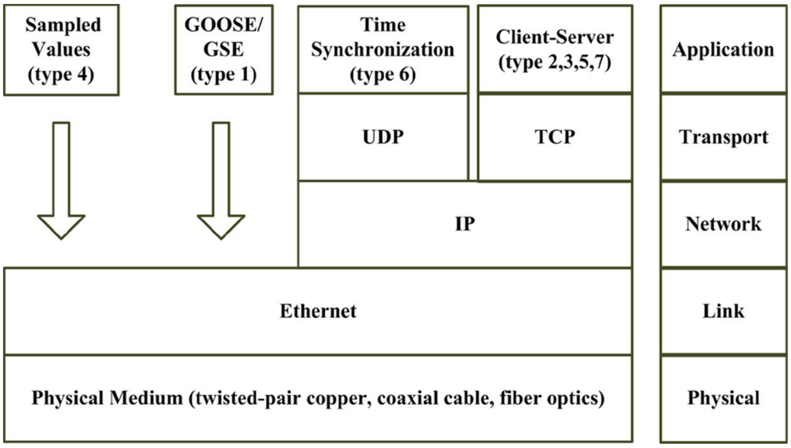

Fig. 1. Message communication stack of IEC 61850.

monitoring, protection, and automation and metering applications are carried out at a 27.6-kV distribution substation site (Section VI).

II. WLAN Technologies for Smart Distribution Substation Applications

Here, we present an overview of the two important smart-grid standards IEC 61850 and IEEE 802.11.

A. IEC 61850 Standard for Substation Automation

IEC technical committee TC57 has published first edition of the standard named as "Communication Networks and Systems in Substation" in 2003 [2], and the second edition of the standard is in progress for power utility. IEC 61850 standard covers not only how to communicate (as a protocol), but also what to communicate (information models). IEC 61850–based substation automation devices should comply the standard communication stack (from Open Systems Interconnection (OSI)-7 layer), as shown in Fig. 1.

In order to achieve appropriate performance of various automation applications, IEC 61850 specifies seven types of messages mapped over the OSI-7 layer stack. The raw data Sampled Value (SV) (type 4), and Generic Object Oriented Substation Event/Generic Substation Event (GOOSE/GSE) (type 1) messages are time critical applications, and therefore, they are directly mapped to second—layer Ethernet data link layer. The medium and low speed messages, e.g., types—2, 3, 5, and 7, are referred to as client/server based Internet Protocol (IP) messages, and mapped over the Transmission Control Protocol/Internet Protocol (TCP/IP) stack. The time synchronization messages (type 6) are broadcasted using the User Datagram Protocol/Internet Protocol (UDP/IP). More details of individual message types can be obtained from IEC 61850 part-5 [2]. The IEC 61850 standard covers wide range of topics divided into ten parts. In addition to first three general parts $(-1, 2, 3)$, the other major parts of this standard utilized in work are: 1) part-5 for communication requirements; 2) part-7 for modeling the information to be communicated; 3) part-8 based GOOSE message communication; 4) part-9 for SV message communication.

B. IEEE 802.11-Wireless LAN Standards

IEEE 802.11 series standardize the WLAN by utilizing unlicensed frequency of Industrial, Scientific and Medical (ISM) radio bands at 2.4 and 5.8 GHz. IEEE 802.11g is the updated version of WiFi standard and can provide data rate up to 54 Mbps. Standard IEEE 802.11a uses the relatively uncluttered 5.8-GHz frequency band and provides a data rate up to 54 Mbps. Newly released IEEE 802.11n standard is intended to increase data rates further, up to 600 Mbps. These WLAN technologies offer flexibility, portability, and low-cost installation over the wired technology which makes it suitable at the distribution substation, where the data rate and performance requirements are less stringent, as well as the cost of technology is more important. Moreover, the quality-of-service (QoS) [21] and advanced security [22] can also be achieved using this technology.

III. Applications of WLAN in Smart Distribution Networks

Potential smart distribution substation applications with performance requirements and the mapping of these smart grid applications to IEC 61850 message types are presented here.

A. Enhancement of Distribution Control and Monitoring

1) Automatic Capacitor Bank Control: The VAR/voltage control device can be used to switch ON/OFF capacitor banks in order to control the reactive power flowing on the system and to maintain the distribution bus voltage. By utilizing WLAN IEDs and industrial AP for this application, not only enhances the control by considering multiple control parameters, but also reduces wiring cost, since performance requirement are not stringent (refer to Table I).

2) Fast Distribution Bus Protection Scheme: A dedicated bus protection may not be economical for medium/low voltage distribution substations. Therefore, the conventional method to protect distribution bus is using overcurrent relays, where the loads on the bus are fed radially (unidirectional power flow). The concept of fast distribution bus protection scheme is shown in Fig. 2, using GOOSE for TRIP and/or BLOCK messages to upstream IED. For example, in case of feeder fault detection

TABLE I
PERFORMANCE REQUIREMENTS FOR SMART-GRID APPLICATIONS IN A DISTRIBUTION SUBSTATION

Smart distribution substation applications	IEC 61850 Message	Allowed delay at distribution (ms)	QoS priority levels
Control & Monitoring			
Automatic Capacitor Bank Control	GOOSE	500-1000	4
LTC Control and Monitoring	GOOSE	250-500	6
Fast Transfer Trip Scheme for Bus	GOOSE	400-500	5
Automation & Metering Application			
Watt/VAR Measurement	IP messages / Sample Values	1000-5000	3
Centralized IED Configuration	IP messages	1000-10000	2
Protection			
Feeder Over current Protection	Sample Value & GOOSE	20	7

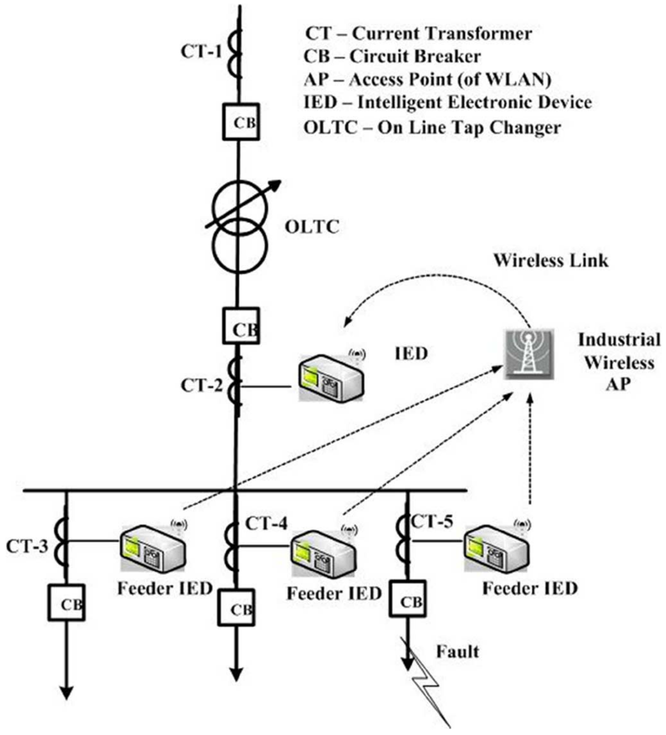

Fig. 2. WLAN communication for fast distribution bus protection.

(shown in Fig. 2), the Feeder IED sends BLOCK command over GOOSE to prevent operation of upstream IED.

3) Load Tap Changer (LTC) Control and Monitoring: The transformer IED can control LTC to maintain the bus voltages within the predefined range. The IEC 61850 GOOSE message can be used to communicate RAISE/DROP the transformer tap settings, which can be well within WLAN average delay. Moreover, the IEC 61850 GOOSE messages with current tap value can be communicated to the transformer IED over the WLAN network, and the restraint slope of the differential protection IED can be adjusted adaptively (according to the tap status).

B. Advancement in Automation and Metering

1) Centralized IED Configuration: The setting or accessing multiple substation IEDs (from the same vendor) using a vendor-specific tool or automatic configuration of all substation IEDs through centralized IEC 61850-6 based substation configurator can easily achieve by exchanging IP files and commands over wireless LAN. This is a fast, easy, and low-cost solution for the noncritical information exchange within the control room.

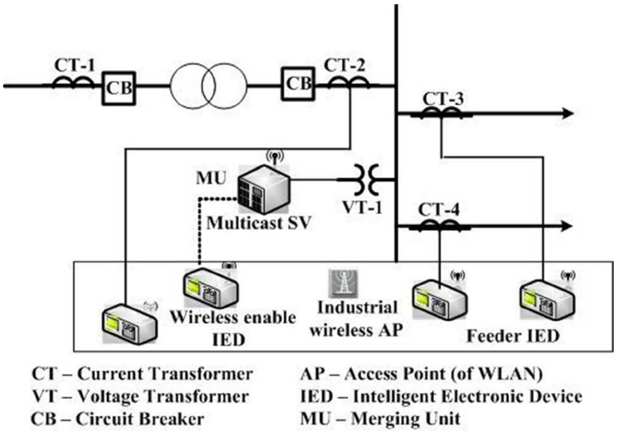

Fig. 3. WLAN communication for watt/VAR measurement.

2) Watt/VAR Measurement by Broadcasting Voltage Phasors: In the distribution substation, it is common to obtain bus voltage at every feeder (breaker) in order to carry out metering of, for example, active/reactive power and power factor, in a feeder IED for all three phases. The anticipated solution for this application is to multicast IEC 61850 sampled value (SV) over WLANs containing all three phase bus voltages from a field device (merging unit) or from a substation control room, where the IED is connected to the bus voltage transformer (VT) as shown in Fig. 3. The multicasting of these IEC 61850–based SV messages over WLANs is not time-critical, and even missing of data for a few seconds is tolerable without affecting the metering applications.

3) Distributed Digital Fault Recording (DFR): Modern protective digital IEDs have capability to record various user-defined signals during an event as a part of data recordings. These digital IED recorders can be triggered to start recording upon detection of a specific event. This concept uses IEC 61850 GOOSE messages over WLANs to trigger all adjacent/corresponding IEDs in order to record all various signals in a substation. This will minimize mesh wiring among substation IEDs, eliminate need of centralize digital fault records, and help to reduce maintenance issues in a substation.

C. Application for Distribution Protection

1) Distribution Feeder Overcurrent Protection: A low-voltage (LV) distribution feeder is normally protected by an overcurrent (inverse definite minimum time (IDMT) characteristic) relays. This protection application is relatively less time critical as the fault current is not significant and IDMT overcurrent coordination always has a backup from upstream relays. The operating time of these relays varies from a fraction of a second to a few seconds. The delay of around several tens of milliseconds is tolerable for this LV overcurrent protection scheme. Moreover, the sampling frequency required

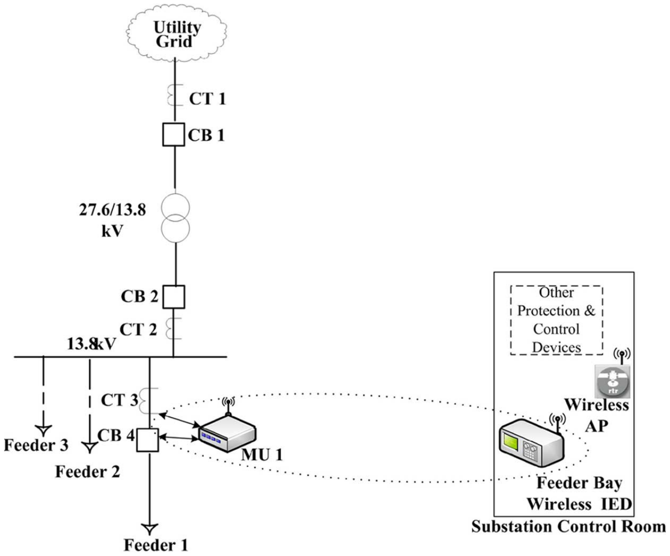

Fig. 4. WLAN for distribution feeder overcurrent protection.

for this LV substation protection is around 480 Hz (eight samples per cycle), which demands less channel bandwidth. The WLAN-based communication network for distribution feeder overcurrent is shown in Fig. 4.

A summary of the smart distribution substation applications discussed above, with corresponding IEC 61850 message types and allowable end-to-end (ETE) delay [2], [12] are tabulated in Table I. Performance class P1 of the IEC 61850-5 standard, which applies to distribution substation bay or to bays with lower performance requirements, is considered for this work.

Furthermore, the enhanced QoS (as per IEEE 802.11e) is implemented by setting 3 b of user priority levels in a 2-byte QoS field from 0 (low) to 7 (high). In this way, various smart-grid application message types can have different priorities/QoS according to the allowed message delay, as shown in the table. Before carrying out performance evaluation of these smart distribution substation applications, it is important to study distribution substation noise levels, as presented in Section IV.

IV. SUBSTATION NOISE MEASUREMENTS AND ANALYSIS

The radio interferences from deliberate or inadvertent external sources may slow down the transmissions of data by causing the WLAN to re-transmit messages. Hence, noise level measurement is important before applying wireless technologies to Air Insulated Substations (AIS). The radio noise sources in a power substation environment can be classified in two different types: 1) Electro-Magnetic Interferences (EMI) from gap or insulation breakdown due to switching operation of Circuit Breaker (CB) or isolator switch, lightning discharge, corona discharge, etc.; 2) Interferences from other radio devices installed within substation or in vicinity of a substation.

In this work distribution substation noise measurements are obtained during circuit breaker operation, on-load operation of isolator switch, and ambient substation noise (includes interferences from other surrounding radio devices). Fig. 5 demonstrates the substation noise measurement setup in a local distribution substation owned by London Hydro Inc, Ontario, Canada. Noise is measured at four different substation locations of 27.6 and 13.8 kV during normal operation, out of which one of the substations is located in the downtown area of the city. Moreover, noise is also measured during the substation events, such as circuit breaker and isolator switch operated at 250 A of full load condition. A commercially available high-resolution Agilent E4404B spectrum analyzer and AirPcap network analyzer are used for the substation noise and interference level measurements in frequency bands of IEEE 802.11 [23].

It is clear from Fig. 6 that, for the band of 2.44–2.5 GHz, the noise level is very low around -110 dBm, while, for the 2.4–2.44-GHz band, due to other sources sending signals on the same band, the noise level is higher up to -70 dBm. Moreover, it is observed that the peaks in noise level (dBm) do not coincide with switching operation of the CB, but these are due to surrounding radio devices.

In addition to noise levels (in dBm), the signal-to-noise ratio (SNR) is also measured using AirPcap. Table II summarizes the results obtained from various scenarios in 13.8- and 27.6-kV distribution substations. It can be observed from the minimum SNR (maximum noise levels) column that there is no significant impact of distribution substation switching events. However, there is a significant impact of other WLAN devices installed in the vicinity of the substation. The detected WLAN-based WiFi networks around the 27.6-kV substation were more compared with 13.8 kV due to the urban area. Hence, the SNR measured in the 27.6-kV substation is more than that in the 13.8-kV substation.

To investigate the impact of the measured noise performance of the substation discussed above on WLAN for smart distribution substation application, the IEC 61850 devices are developed during this work, as will be discussed in Section V.

V. PROTOTYPES DEVELOPMENT OF WLAN-ENABLED IEC 61850 DEVICES IN A LABORATORY

An industrial embedded system is used to develop wireless enabled IEC 61850 devices in a laboratory. This industrial embedded system is equipped with: 1) Intel's DH55HC ATX mother board with 3.2 GHz processor; 2) ANTEC's industrial 3U rack-mount chassis; 3) CISCO's Linksys WMP600N wireless LAN Network Interface Card (NIC) with IEEE 802.1i protocol and up to 128-bit encryption for cyber security; and 4) QNX Real-Time Operating System (RTOS). Hard-real time performance of the IEC 61850 devices is achieved with the help of various capabilities of the real-time platform, such as hard real-time timers, multithreads for parallel processing, and input/output packet (*io-pkt*). Moreover, a WLAN communication card driver is developed using *libpcap* library functions.

Normally, the round-trip time (RTT) of communication messages is measured in order to evaluate the performance of the communication network. Hence, two WLAN-enabled IEDs are developed to study RTT for various IEC 61850 messages: 1) *Processing-IED* and 2) *Echo IED*. These IEDs resemble the functionality of any IEC 61850-based devices communicating control, monitoring, or metering application (GOOSE or client/server-based IP) messages. The *Processing-IED* sends IEC 61850 messages with a unique ID and registers sending time using hard-real time timers. On the other hand, *Echo-IED* upon reception of the IEC 61850 messages, it echoes back the same message to the *Processing-IED*. Finally, *Processing-IED*

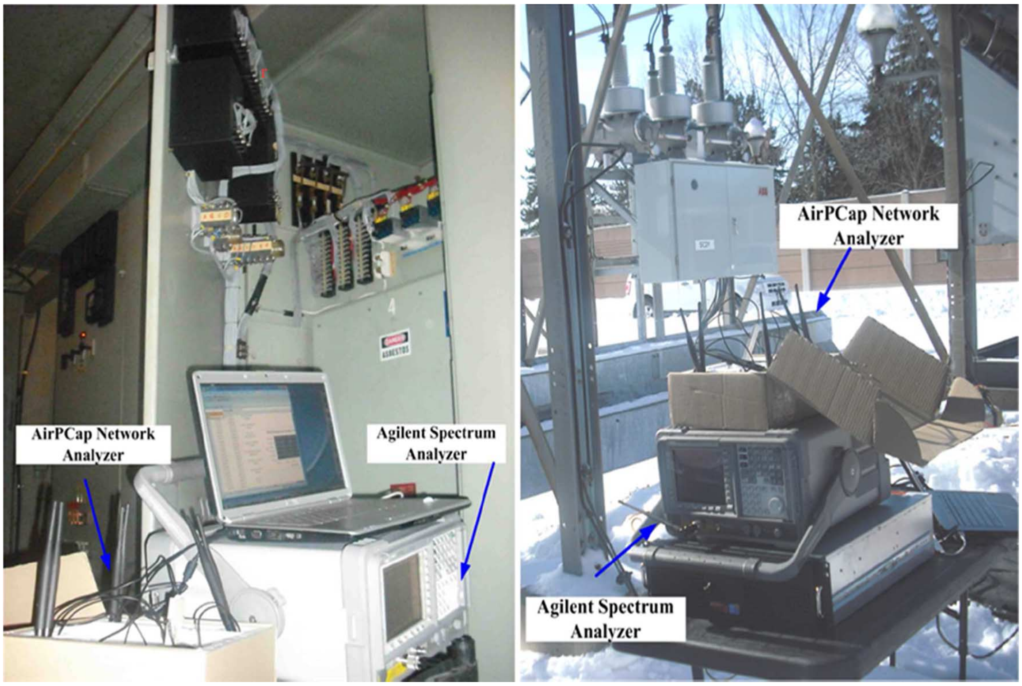

Fig. 5. Noise measurement setup close to 13.8 kV and 27.6 kV switchgears at London Hydro distribution substation.

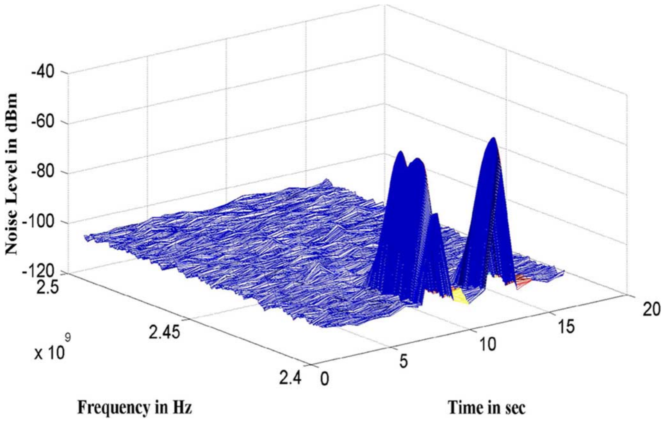

Fig. 6. 3-D plot for the noise measurement in 2.4-GHz bands.

TABLE II
RESULT SUMMARY OF NOISE MEASURED WITHIN DISTRIBUTION SUBSTATIONS

Substation Scenario	Min. SNR (dB)	Max. SNR (dB)	Avg. SNR (dB)
13.8 kV substation without switching	17	36	31
13.8 kV Substation With CB switching	16	38	32
27.6 kV substation without switching	14	24	18
27.6 kV substation with CB switching	15	26	19
27.6 kV substation with isolator switching operation	13	24	19

matches the unique ID of the IEC 61850 message and calculates RTT by subtracting receiving time of the echo-back IEC 61850 message with the registered sending time of the same IEC 61850 message.

Furthermore, in order to investigate the performance of earlier discussed distribution protection application, the developed IEC 61850-based devices are: 1) MU playback and 2) protection and control (P&C) IED. The MU playback communicates the IEC 61850 sampled value messages (which include current/voltage signals obtained from PSCAD/EMTDC simulation) to the P&C IED. The P&C IED implements inverse overcurrent protection functions. In the case of short-circuit fault condition on the component to be protected (i.e., distribution feeder in this case) by protection IED, the protection IED issues a trip command to the circuit breaker using an IEC 61850 GOOSE message. Upon receiving IEC 61850 GOOSE, the MU calculates total protection time by subtracting GOOSE receiving time with sending time of SV message which corresponds to the fault inception time. Detailed functionalities of these four prototypes of IEC 61850 devices are described below:

A. Development of Wireless Processing IED

Fig. 7 illustrates the functional diagram of a *Processing-IED* with the major function blocks only. As depicted in Fig. 7, the processing IED has two separate real-time threads implemented using RTOS. These threads are executed in parallel, such that *Processing-IED* can send or receive IEC 61850 messages simultaneously. Thread-1 functions are executed for sending IEC 61850 messages at regular intervals, whereas thread-2 captures the IEC 61850 message and computes the total RTT/message delay over the WLAN. As part of thread-1, each IEC 61850 message has the following IEC 61850 compliance WLAN settings: 1) WLAN medium access control (MAC) address; 2) basic service set (BSS) ID; 3) *EtherType*/IEC 61850-based Application ID (*AppID*); and 4) unique message ID/counter. WLAN MAC addresses specify source and destination MAC

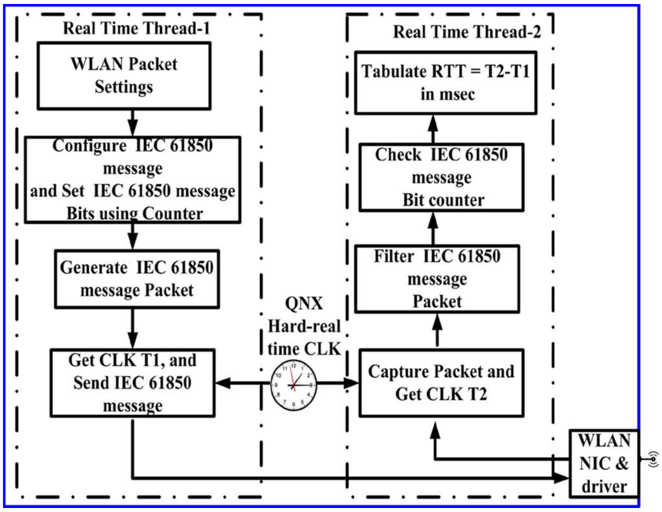

Fig. 7. Functional block diagram of the developed wireless processing IED.

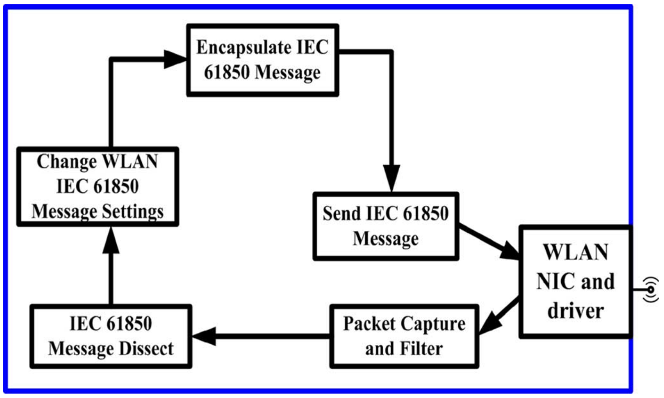

Fig. 8. Functional block diagram of the developed wireless echo IED.

addresses, and BSS ID is applied according to AP of the WLAN.

IEC 61850 has already specified AppID in order to identify IEC 61850 protocol and message type. Moreover, each IEC 61850 message has been stamped with a unique identification number using a digital counter in order to compute the RTT. The second function of thread-1 configures IEC 61850 message and stamps a unique packet ID. Thereafter, the IEC 61850 message is scheduled for transmitting over the WLAN. The time of each message transmission (T1) is registered in the internal buffer using the hard real-time clock (CLK) of RTOS. The thread-2 of *Processing IED* is continuously reading the WLAN NIC card for new packets and stores the reception time (T2) for each IEC 61850 message using QNX CLK. The next function is to filter out IEC 61850 message and identify packet ID/counter. From the packet ID, thread-2 pulls message sent time (T1) and subtracts received time with the sent time to compute total RTT.

B. Development of Wireless Echo-IED

Fig. 8 describes the major functions developed for the *Echo-IED*.

Upon reception of a packet from the *Processing-IED* by the packet capture function from WLAN transceiver driver, the *Echo-IED* filters for the IEC 61850 message, and the received IEC 61850 messages are dissected to sweep source and destination addresses. Finally, the message is encapsulated and scheduled to send it back to *Processing-IED* over a WLAN.

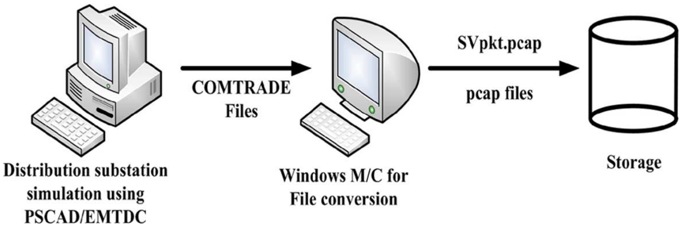

Fig. 9. Offline generation of IEC 61850 SV messages.

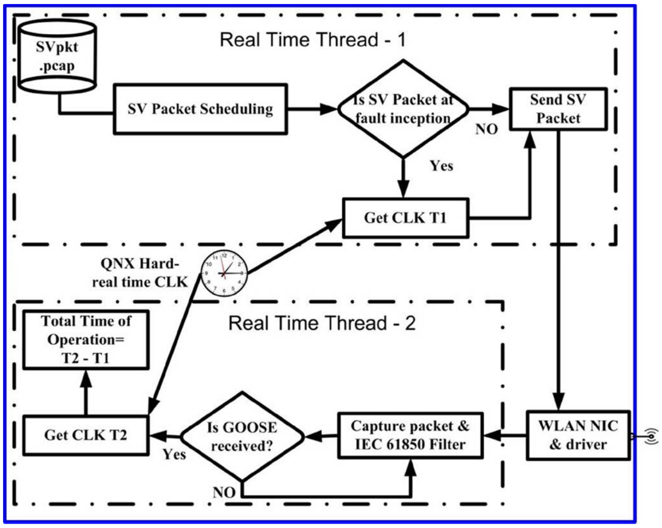

Fig. 10. Functional block diagram of the developed wireless MU.

C. IEC 61850-Based Wireless MU Playback

Fig. 9 illustrates the flow diagram of obtaining current signals from the PSCAD/EMTDC simulation tool and converting these data streams into IEC 61850 SV messages. The power system model of a distribution substation, and various short-circuit scenarios are simulated using PSCADE/EMTDC. The current signals for all of these simulated scenarios are recorded using the standard COMTRADE file format. On a Windows machine, the IEC 61850 SV messages are configured, including WLAN packet settings, and converted COMTRADE data into captured packet file format "**.pcap*" using *libpcap* tool in offline at a desired sampling rate.

The merging unit is implemented as a real-time data playback as shown in Fig. 10. Once the *SVpkt.pcap* file is prepared offline, the QNX target machine can schedule the SV packet delivery, as explained in [24].

Two separate threads are implemented to develop MU playback. Thread-1 schedules SV streams of WLAN data at 480 Hz and registers the QNX CLK time of SV message corresponding to fault inception (T1). Thread-2 captures WLAN messages and filter IEC 61850 GOOSE, upon reception of GOOSE (Trip) message from protection IED, the MU calculate the time difference between first SV message corresponding to fault sent and the GOOSE/Trip message received.

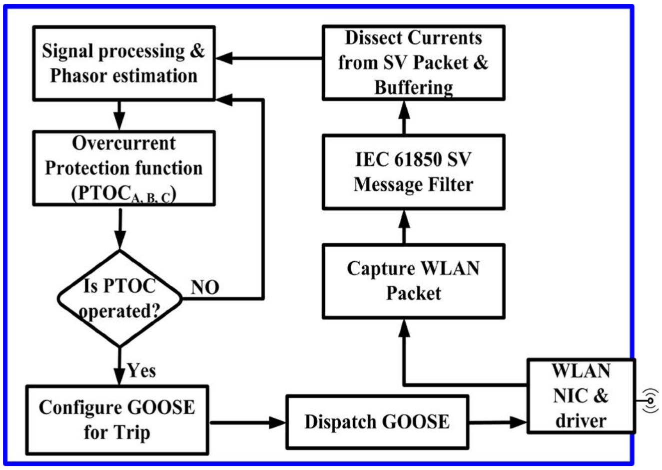

Fig. 11. Protection and control IED functional block.

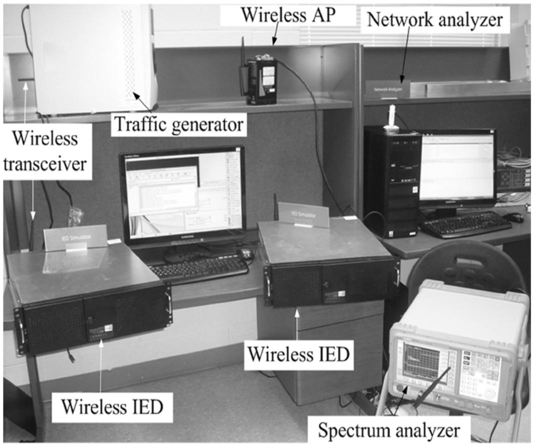

Fig. 12. WLAN setup within the laboratory.

D. IEC 61850-Based Wireless P&C IED

The P&C IED developed for distribution feeder protection is illustrated in Fig. 11. The digital overcurrent protection algorithm is developed based on [25], [26]. Once protection IED opens communication port with WLAN NIC driver using *libpcap*, it starts capturing packet over WLAN network and filters the packet for IEC 61850 SV messages.

The current signal value is dissected from each SV message and stored in buffer. The short-circuit condition is detected, and the time of operation is determined by time overcurrent protection function (i.e., PTOC Logical Nodes of IEC 61850) as discussed in the Appendix. The IEC 61850 GOOSE message is configured to send TRIP signal to the MU.

VI. LABORATORY TESTING, RESULTS, AND DISCUSSION

Fig. 12 shows the laboratory test setup to investigate the performance of WLAN for IEC 61850-based distribution substation.

The prototypes of substation protection and automation devices (as a part of substation control room) are deployed in the laboratory include wireless IEDs, wireless AP, spectrum analyzer, network analyzer, and traffic generator as shown in the figure.

The field devices, such as MU and radio noise generation sources, are installed outside the laboratory (not shown in the figure). Wireless IEDs, MUs,, and traffic generator are developed using industrial embedded computers with a real-time platform as discussed in the previous subsection. The commercial wireless AP designed for the substation environment is used in this setup. The wireless AP [27] facilitates the communication among wireless IEDs within the WLAN. Moreover, an industrial wireless AP also allows security networks based on IEEE 802.11i [22], IEEE 802.1X/RADIUS for wireless user traffic and distributing dynamic encryption keys, and QoS based on IEEE 802.1Q. Hence, the developed industrial WLAN in the laboratory not only enhances network security, but also facilitates reliable communication links, and additional noise attenuation features, which are very promising for next-generation communication infrastructure for the smart grid. A spectrum analyzer is used to measure radio noise and interference levels within the setup [23]. AirPcap with Pilot tool is used as a network analyzer to analyze and monitor the substation WLAN [28]. A network analyzer is configured in the promiscuous mode to sniff all of the packets from the entire IEEE 802.11-based WLANs. It captures all of the data packets from the network and displays all various statistics of network traffic, signal, and noise strength at each wireless transceivers. The different levels of electromagnetic interferences are generated using microwave ovens and cordless phones, whereas RF interferences from other WLAN devices are obtained using a wireless traffic generator which can inject various types of messages over different WLAN channels.

As listed in Table I, the smart distribution substation applications are classified in three types of IEC 61850-defined messages, such as sampled values and GOOSE messages directly mapped to data link layer and client/server IP messages over TCP/IP. A remote MU (installed outside the laboratory) communicates SVs and client/server messages to wireless P&C IED within the corresponding BSS. A P&C IED sends GOOSE messages to MU. Moreover, processing and echo IEDs exchange client/server IP and GOOSE messages using wireless AP.

A. Laboratory Testing of Distribution Control and Monitoring Applications

To study the performance of IEC 61850-based WLAN for control and monitoring applications, the RTT of the GOOSE message is measured by setting up *Processing*- and *Echo-IEDs* in the described laboratory setup. Different data rates offered by WLAN technologies, i.e., 1, 11, and 54 Mbps, are considered for this analysis. Fig. 13 shows the GOOSE RTT over WLAN at 1-, 11-, and 54-Mbps data rates. It is observed that, with 1 Mbps, the average delay of GOOSE is 4.1 ms, whereas the maximum delay is around 15.2 ms. For 11 Mbps, the average and maximum GOOSE RTT delays are 3.8 and 6.7 ms, respectively. It can also be inferred from Fig. 13 that, with a higher data rate of 54 Mbps, the maximum delay reduces to 4.2 ms, and the average delay is around 3.5 ms. Further investigation is carried out at 54 Mbps.

Testing is done to analyze the time-critical GOOSE message delays for various noise levels. The SNR is measured using AirPcap network analyzer in the laboratory, and different noise levels are generated using microwave ovens, cordless phones, and traffic generators. The noise sources are turned ON/OFF

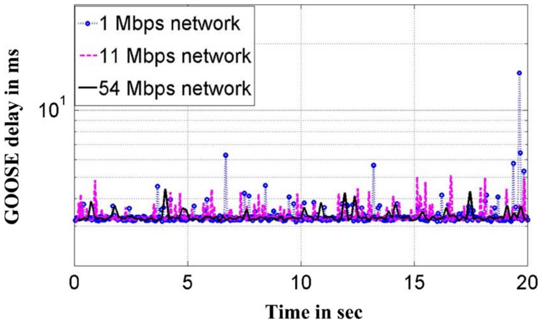

Fig. 13. GOOSE RTT delay with different WLAN data rates.

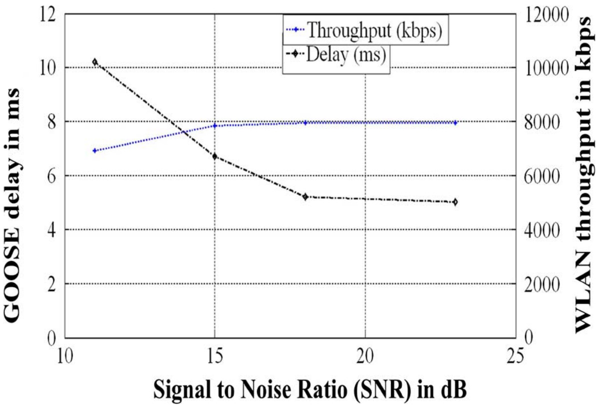

Fig. 14. GOOSE delays with various noise level and throughput.

during the performance study to closely create various noise profiles measured in the distribution substations (e.g., Fig. 6) in a laboratory environment. It can be observed from Fig. 14 that the GOOSE message delay increases from 5 to 10.2 ms, as well as, the throughput of WLAN reduce to 6930 Kbps as the SNR reduces from 23 dB to 11 dB. The noisy environment causes higher bit-error-rate in a message, and therefore, the message may be discarded at the receiver. Thus, the same message has to be retransmitted over the network, which can cause higher delays. The delays obtained for the GOOSE messages are still within the allowable time delay requirements (10 ms ETE delay or 20 ms RTT).

B. Lab Testing of Automation and Metering Applications

Testing of RTT/message delay for automation and metering applications is carried out using IP message communication between *Processing*- and *Echo-IEDs* as a part of the discussed laboratory setup.

As shown in Fig. 15, the average delay of the message communication is 167 ms, whereas the maximum delay is 320 ms for a 1-Mbps data rate. Similarly, the maximum delay of IP message is around 102 ms, and average delay is 28 ms.

It can also be observed from Fig. 15 that the maximum RTT of IP messages for the 54-Mbps data rate is 26 ms and average delay is 23.5 ms. The IP messages experiences higher communication delay due to low priority (as per QoS). It can be inferred that the network delay is more stable and smooth with 54 Mbps, as compared with previous 1- and 11-Mbps data rates.

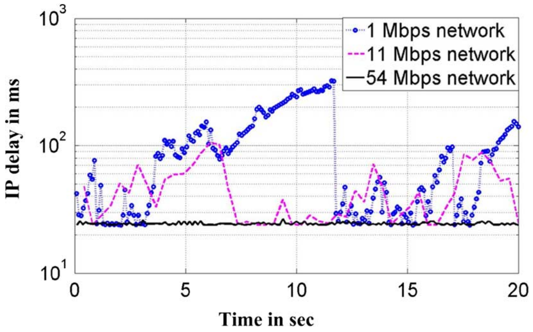

Fig. 15. IP message delay at different data rates.

TABLE III
OVERCURRENT ELEMENT OPERATING TIME $\mathrm{M} = 7$, A-G FAULT

TDM	Over current Relay Operating Time (AG Fault)			
	MATLAB simulation (no comm. delay) (in sec)	From hardware testing (in sec)	Difference (comm. delay) (in sec)	Difference in Percentage (%)
0.05	0.19373	0.201	0.00727	3.75
0.10	0.30833	0.3228	0.01452	4.71
0.20	0.5375	0.561	0.0235	4.37
0.40	0.995833	1.012	0.01616	1.62
0.60	1.4521	1.472	0.020015	1.37
0.80	1.91041	1.925	0.01459	0.76
1.00	2.531	2.55	0.01938	0.77

C. Laboratory Testing of Protection Application

The P&C IED is installed within laboratory, whereas MU is moved to remote location from the laboratory as shown in Fig. 12. The communication of SV stream of messages from MU to P&C IED is initiated. The MU is streaming data packets with digitized voltage and current signals at 480 Hz (eight samples per cycle), which is specified as the preferable sampling rate for distribution substation according to the IEC 61850-5 standard. The operating time of the A-phase element is tested for various time-division multipliers (TDMs), where the multiple of pick-ups (M) is 7, with A-phase line to ground (A-G) fault. Table III demonstrates the results of over-current protection element performance over wireless LAN. The protection operating time using MATLAB simulation only includes execution of IDMT logic part (of the algorithm explained in the Appendix), and hence it does not include communication and hardware related delay components.

It can be observed from the table that the maximum difference between time of operation obtained from MATLAB (which does not include any communication delay) and WLAN field setup (including WLAN communication delay) is 4.71% (14.52 ms), which is not significant for distribution substation protection.

VII. FIELD INVESTIGATION RESULTS AND DISCUSSION

Here, we present the assessment of WLAN-enabled devices in a harsh environment of distribution substations. Several substation site visits are conducted at 13.8- and 27.6-kV substations in the London, ON, Canada, area owned by London Hydro Inc. The field testing results presented in this paper are

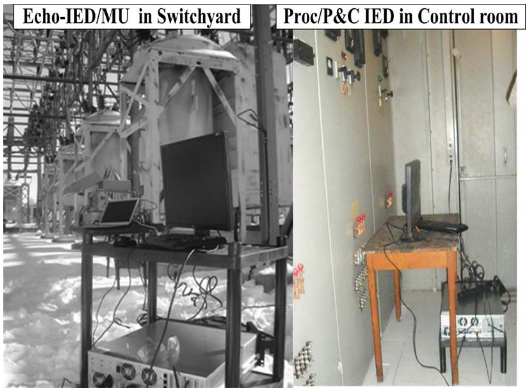

Fig. 16. Field testing setup in 27.6-kV distribution substation.

TABLE IV
GOOSE DELAYS WITH VARIOUS SWITCHING INSTANTS

Scenario	Avg. Delay (ms)	Max. Delay (ms)
27.6 kV substation-1 without any switching operations	3.5	6.8
27.6 kV substation-1 with SF6 CB switching	3.6	7.47
27.6 kV substation-2 without switching	3.4	7.52
27.6 kV substation-2 with oil-tank CB switching	3.5	7.51
27.6 kV substation-2 with isolator switching	3.7	6.91

obtained using WLAN IEDs installed in two 27.6-kV substation switchyards at one end and in the control room at another end. The distance between these two WLAN devices (control room to switchyard) is approximately 75 m. The performance of GOOSE, overcurrent protection, and client/server communication is demonstrated below. Fig. 16 shows the on-site measurement setup at the 27.6-kV London Hydro distribution substation.

A. Field Results for Monitoring and Metering Applications in 27.6 kV

Table IV shows the average and maximum RTTs for GOOSE messages used for various applications in the 27.6-kV distribution substation.

It can be observed that switching of (SF6 and oil tank) circuit breakers do not have significant impact on the average delay of GOOSE messages. Moreover, the maximum delay registered for this substation is around 15 ms, which is within the allowable range of the IEC 61850 standard.

B. Field Results for Monitoring and Metering Applications in 27.6 kV

Various client/server applications are tested in a 27.6-kV London Hydro, Inc., distribution substation. For this analysis, processing-IED is setup in the control room, and echo-IED is configured close to the 27.6-/13.8-kV transformer. Various IP packets are communicated between substation control room and switchyard over WLAN. The results obtained from this testing are discussed below.

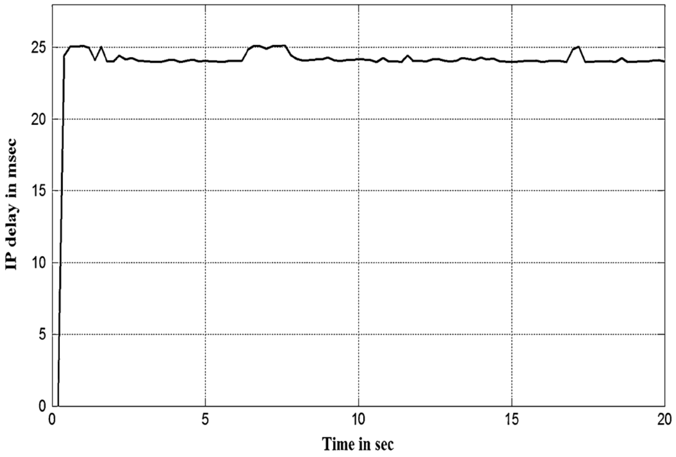

Fig. 17. Delay of client/server messages.

TABLE V
OVERCURRENT ELEMENT OPERATING TIME $M = 7$, Fault Type = A–G

TDM	Over current Relay Operating Time (AG Fault)			
	From MATLAB simulation (in sec)	From Wireless LAN hardware Testing (in sec)	Difference between hardware and simulation (in sec)	Difference Percentage (%)
0.05	0.19373	0.194727	0.00927	4.78
0.10	0.30833	0.326058	0.017728	5.75
0.20	0.5375	0.555076	0.017576	3.26
0.40	0.995833	1.01176	0.015927	1.6
0.60	1.452083	1.500	0.047191	3.25
0.80	1.910411	1.9634	0.052987	2.77
1.00	2.513360	2.544776	0.031416	1.25

Fig. 17 shows the RTTs of client/server (IP) messages. It can be observed that IP messages (for client/server applications) have an average delay of 24 ms, whereas the maximum delay is around 25.1 ms.

C. Field Results for Overcurrent Protection Applications

The wireless protection IED with an overcurrent element is installed in a control room of a 27.6-kV substation. On the other side, wireless MUs are sending SV messages to the protection IED is kept in the field. The result for the overcurrent element operation is tabulated in Table V for the A-G fault element.

It can be inferred from the results the difference between the overcurrent relay operating time, from MATLAB simulation and from WLAN hardware testing in terms of milliseconds, which is considerable, as overcurrent relay operating time is in terms of seconds. Also, the maximum percentage difference due to WLAN communication delay is 5.75% (17.73 ms), which should be acceptable at less critical LV distribution-level applications.

VIII. CONCLUSION

Smart distribution substations is one of the key elements to realize the vision of a green, safe, and reliable smart grid. With the recent advancements in industrial WLAN technologies, it is considered to be one of the potential technologies for IEC 61850-based smart grid. Several smart control, monitoring, and protection applications of WLAN in IEC 61850-based smart distribution substation are identified and its performance requirements are discussed in this work. The radio noise interferences are measured in London Hydro's 13.8- and 27.6-kV substations. The average SNR measured from the various scenarios in 13.8- and 27.6-kV substations are 31 and 18 dB, respectively, mainly due to surrounding radio devices. Details of hardware prototypes development of four WLAN-enabled IEC 61850 devices are presented using industrial embedded computer with a hard real-time operating system. The *Processing-IED* and *Echo-IED* are developed to analyze the RTT of IEC 61850-based communication message/information exchange for control and automation applications, using IEC 61850 messages. Moreover, the protection and control IED and merging unit playback are developed to investigate delay incurred over the WLAN for LV feeder over current protection. From laboratory setup at a 45-m distance between IEDs, the average RTT of smart distribution substation control applications (GOOSE message) is 3.5 ms, whereas, for automation applications (IP messages), it is 23.5 ms at a 54-Mbps data rate. The maximum percentage of operating time of over current protection is 4.71%, and corresponding delay is 14.52 ms. The average radio noise level should be higher than the threshold which can result into low throughput and higher delay, which is identified as 16 dB in this study. Finally, the field testing of a 54-Mbps WLAN is carried out by installing the developed prototype devices in harsh-environment of a 27.6-kV substation at 75-m distance. The maximum GOOSE RTT observed in distribution substation is 15 ms, and for IP message RTT is 24 ms. The maximum percent of communication delay for LV feeder overcurrent protection is 5.75% with a corresponding delay of 17.72 ms, which is within limit of total allowable delay of few tens of milliseconds. This comprehensive investigation using laboratory and field tests demonstrate suitability of an industrial WLAN for some of the presented innovative smart-distribution substation applications.

APPENDIX

The functional flowchart of digital overcurrent protection element implemented in a wireless protection IED is shown in Fig. 18.

The digital overcurrent protection algorithm is developed based on [25] and [26]. The SV data loss can be handled using SV estimation/interpolation algorithm explained in [4]. The digital values of all three phase and neutral current signals are dissected from SVs, and the mimic (differentiator) filter is applied on these raw data streams to remove decaying dc components from current signals. The rms values of the currents are estimated from real and imaginary components of the phasors (obtained using discrete Fourier transformation filters for real and imaginary parts) using piecewise linear approximation technique. The values of coefficients (i.e., x and y) for two region approximations are multiplied with large (L) and small (S) components of the current phasors, and the multiple of pickup (Mj) is calculated by taking the ratio of current rms with its pickup (i.e., settings of overcurrent element), which is part of the protection operating time (tj) equation of inverse-time-overcurrent characteristics. To determine the time delay corresponding to the current in the protected equipment, the integration/sum of all instant of operating time (tj) at sampling frequency (time difference) need to be carried out.

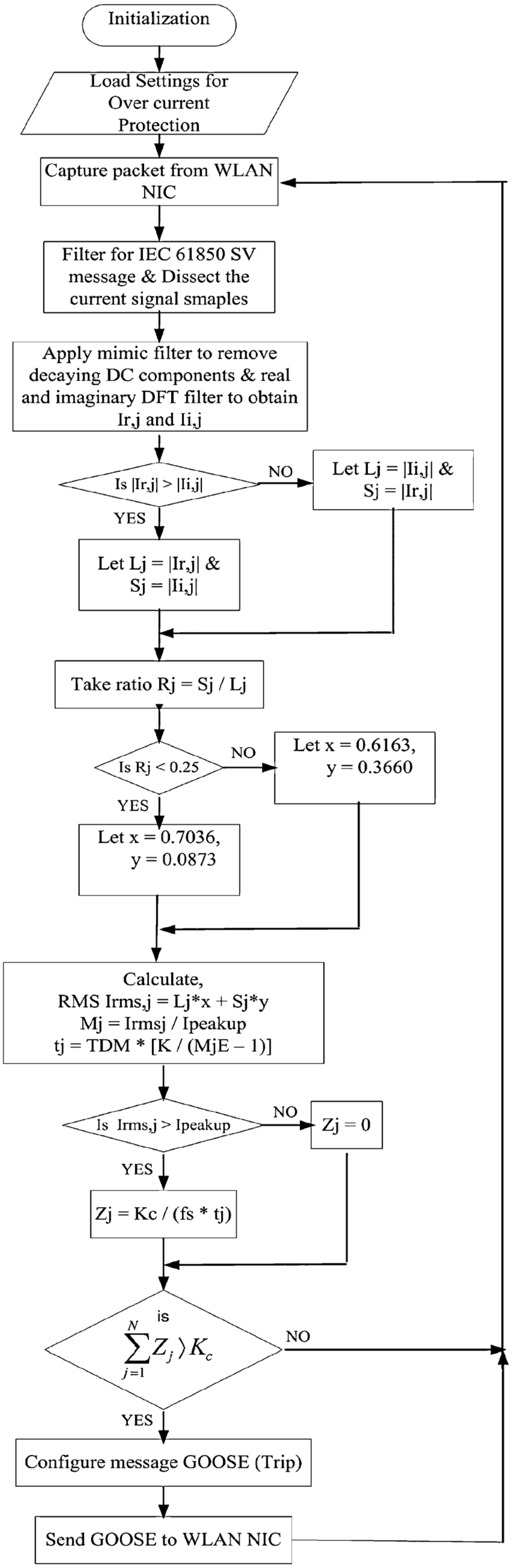

Fig. 18. Overcurrent algorithm implemented in protection IED.

Finally, if this summation/integration is higher than operating area (Kc) then overcurrent element picks-up. This pickup of overcurrent protection element is communicated to MU over wireless LAN using IEC 61850 GOOSE. Therefore, the overcurrent trip bit is set to high in a GOOSE message, and it is retransmitted several times using WLAN NIC.

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