An Empirical Study of Communication Infrastructures Towards the Smart Grid: Design, Implementation, and Evaluation

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***Abstract*—The smart grid features ubiquitous interconnections of power equipments to enable two-way flows of electricity and information for various intelligent power management applications, such as accurate relay protection and timely demand response. To fulfill such pervasive equipment interconnects, a full-fledged communication infrastructure is of great importance in the smart grid. There have been extensive works on disparate layouts of communication infrastructures in the smart grid by surveying feasible wired or wireless communication technologies, such as power line communications and cellular networks. Nevertheless, towards an *operable, cost-efficient and backward-compatible* communication solution, more comprehensive and practical understandings are still urgently needed regarding communication requirements, applicable protocols, and system performance. Through such comprehensive understandings, we are prone to answer a fundamental question, *how to design, implement and integrate communication infrastructures with power systems*. In this paper, we address this issue in a case study of a smart grid demonstration project, the Future Renewable Electric Energy Delivery and Management (FREEDM) systems. By investigating communication scenarios, we first clarify communication requirements implied in FREEDM use cases. Then, we adopt a predominant protocol framework, Distributed Network Protocol 3.0 over TCP/IP (DNP3 over TCP/IP), to practically establish connections between electric devices for data exchanges in a small-scale FREEDM system setting, Green Hub. Within the real-setting testbed, we measure the message delivery performance of the DNP3-based communication infrastructure. Our results reveal that diverse timing requirements of message deliveries are arguably primary concerns in a way that dominates viabilities of protocols or schemes in the communication infrastructure of the smart grid. Accordingly, although DNP3 over TCP/IP is widely considered as a smart grid communication solution, it *cannot* satisfy communication requirements in some time-critical scenarios, such as relay protections, which claim a further optimization on the protocol efficiency of DNP3.**

***Index Terms*—Communication infrastructures, DNP3 over TCP/IP, field deployment and performance evaluations, FREEDM systems, smart grid, system design.**

I. Introduction

ENERGY IS THE life blood of modern civilizations and has enormously boosted the development of the world economy and human society. Today, the majority of energy consumed is from three main fossil fuels, coal, petroleum and natural gas. These three together supply more than 85% of the world's energy consumption [1]. Nevertheless, due to the non-renewable and non-environmentally-friendly features of fossil fuels, more and more society and environment problems are emerging: rapid increases of fuel prices, greenhouse gas emissions from fuel combustion, acid rain, and so on.

To address these issues, non-polluting renewable energy resources, such as solar, wind and hydrogen, are extensively proposed as alternative resources [2], [3] to deal with the emerging energy crisis associated with fossil fuels. Yet aiming for higher shares of distributed renewable energy in end-users' energy consumptions, the current power system, which is suffering from transmission and distribution losses and vulnerable to power outages [4], is unlikely to meet challenges on system efficiency and stability [5] when delivering renewable energies. To this end, upgrading the aging power system towards the smart grid is imperative by integrating efficient communication infrastructures with power systems for timely system monitoring and control [6]. Within the upgraded system, power equipments are interconnected to practice a brand new power management paradigm, that is, utilizing bidirectional information flows to drive bidirectional electricity flows. In this way, we can significantly mitigate impacts of variability and uncertainty of renewable resources and dramatically improve energy efficiency. Hence, a full-fledged communication infrastructure is critical for high penetration integrations of distributed renewable energy resources in the smart grid.

To build an efficient communication infrastructure, intensive studies are currently underway across diversified perspectives. [7]–[11] investigate communication requirements and corresponding system architectures, while [12], [13] survey feasible communication technologies and applicable standards for communications in the smart grid. Even though such broad surveys and technical reviews, there still lack clear understandings and pertinent experiences on a fundamental question, *how to design, implement, and practically integrate efficient communication infrastructures with power systems*. Towards an *operable, cost-efficient, and backward-compatible* communication solution, such a fundamental question should be elaborated in three critical aspects, including detailed communication

Manuscript received March 31, 2012; revised September 05, 2012; accepted October 02, 2012. Date of publication February 13, 2013; date of current version February 27, 2013. This work was supported by ERC Program of the National Science Foundation under Award Number EEC-0812121. Earlier versions of this work were published in the 2011 IEEE Global Communication Conference (Globecom'11), the 2011 IEEE Smart Grid Communication Conference (SmartGridComm'11) and in the demo session of the 18th Annual International Conference on Mobile Computing and Networking (Mobicom'11). Paper no. TSG-00167-2012.

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Digital Object Identifier 10.1109/TSG.2012.2225453

requirements, applicable protocols and schemes, as well as satisfactory system performance. In this paper, we address these concerns in a synthetic empirical study of a smart grid demonstration project, the Future Renewable Electric Energy Delivery and Management (FREEDM) systems [14], which are envisioned to demonstrate the generation, distribution, storage, and management of renewable energy resources. More specifically, we firstly clarify communication requirements implied in communication scenarios of FREEDM systems. Based on summarized communication requirements, we then adopt an extensively recommended protocol framework, DNP3 over TCP/IP, to practically establish data links between electric devices in a small-scale FREEDM system setting, Green Hub. Within the real-setting Green Hub testbed, we measure message delivery delays to indicate the system performance of the DNP3-based communication infrastructure.

Our results reveal that timing requirements of message delivery are primary concerns in the smart grid communication, which are claimed by distinct power management applications, ranging from several milliseconds in the relay protection [15] to several minutes in regulations of load balancing [7]. Moreover, diversified timing requirements significantly dominate applicabilities of protocols and schemes in communication infrastructures. As a result, we derive contradictory, yet interesting conclusions about applicability of the DNP3 over TCP/IP framework in the smart grid regarding variable timing requirements. On the one hand, DNP3 is a viable protocol for real-time monitoring applications although it is a legacy Supervisory Control and Data Acquisition (SCADA) protocol. However, on the other hand, in spite of a recommended communication solution, DNP3 misses quite a few time-critical applications due to complicated protocol designs, thereby needing further optimizations in response to a high delay efficiency. Overall, a well-defined communication infrastructure undertakes information exchange responsibilities among synergetic power equipments. Unsatisfactory communication performances not only limits the achievement of smart grid visions on energy managements, but poses potential damages on the power system.

The rest of this paper is organized as follows. Section II describes FREEDM system overviews, including system objectives, application use cases, communication scenarios, and communication requirements. In Section III, we present the system architecture of a small-scale FREEDM system testbed, Green Hub, as well as implementations of a DNP3 over TCP/IP based communication infrastructure across electric equipments. Detailed experimental results are discussed in Section IV. Finally, we conclude this paper in Section V.

II. FREEDM VISIONS

In this section, we firstly present a system overview of the envisioned FREEDM systems, then summarize communication requirements across typical FREEDM use cases.

A. System Overview

FREEDM systems [14] envision a revolutionary power grid to facilitate high penetration integrations of distributed renewable energy resources towards the smart grid. As shown in Fig. 1, residential users in FREEDM systems are able to supply energy demands with distributed renewable energy generators installed in their houses, such as solar panels and wind turbines. These energy generators, together with residential energy storage facilities, like batteries and electrical vehicles [16], make conventional energy customers to be energy providers by selling excess energy to the public through FREEDM systems. Accordingly, an *Energy Internet* is formed across interconnected users to exchange information and share energy in bidirectional manners. To fulfill *bidirectional* energy and information flows, FREEDM systems focus on power distribution systems to integrate residential energy generators in a brand new architecture through advanced power electronic equipments and efficient communication infrastructures.

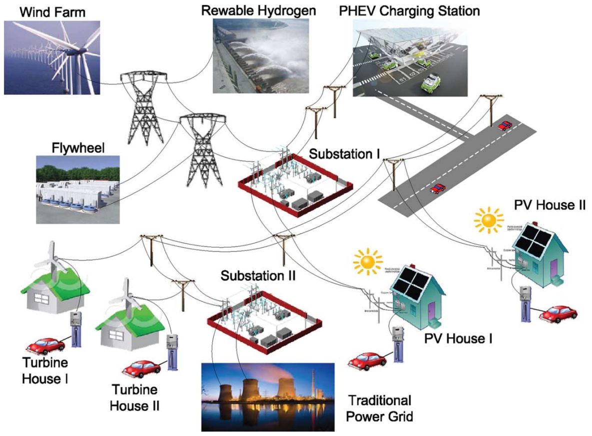

Fig. 1. Envisioned FREEDM systems.

Fig. 2 shows a FREEDM-compatible architecture for future power systems, in which multiple power distribution systems, named as "Zone", are emanating from a 69 kV[1] power transmission system to retrieve a step-down voltage for end users. Within diverse zones, some follow FREEDM visions, such as Zones A and C, named as "FREEDM zones," while others still work as traditional distribution systems, such as Zones B and D. Since a FREEDM zone is composed of several residential houses that are geographically close, it also indicates a "FREEDM community," where residents operate renewable energy facilities coordinately for energy sharing.

To manipulate a FREEDM zone, two equipments are crucial, including the Intelligent Energy Management (IEM) and the Intelligent Fault Management (IFM). The IEM aims to exploit real-time equipment monitoring for local energy managements, such as on-demand routing energy, interfacing various loads, and so on [14]. These energy management functions are achieved by an advanced power electronic equipment, the Solid State Transformer (SST) [18], which is integrated to undertake responsibilities of electricity transforming with different outputs [direct current (dc) or alternating current (ac)], different voltage levels, and different power quality levels [14]. Apart from the underlying SST, an IEM also involves Distributed Grid Intelligence (DGI) as the software platform, which is more related to control operations in response to various system situations, such as electricity dispatching and feeder reconfigurations [14]. The IFM is designed to identify and isolate unexpected

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[1] A commonly used voltage for overhead power transmission lines in North America [17].

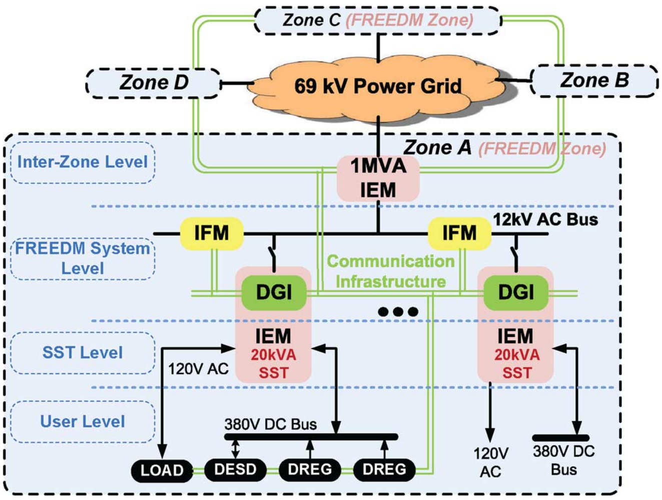

Fig. 2. System architectures for a FREEDM-compatible power system.

faults for system stability maintenances, which is established on a Fault Isolation Device (FID) [19] and also controlled by the DGI platform.

With IEMs and IFMs, residential renewable energy generators are prone to be organized in a "FREEDM Community" as shown in Zone A of Fig. 2. Zone A is a 1 MVA FREEDM system instance that entails that the total power of all loads in Zone A is 1 MVA. At the entrance of the FREEDM zone, a 1 MVA IEM is installed as the interface between 69 kV ac transmission lines and 12 kV[2] ac distribution lines. In the FREEDM zone, the 12 kV distribution bus hooks multiple IFMs for line protections and five 20 kVA IEMs in a loop manner for energy sharing. Each 20 kVA IEM is mapped to a residential house to manage all renewable energy facilities at home, including loads, Distributed Energy Storage Devices (DESD) (i.e., batteries and electrical vehicles), and Distributed Renewable Energy Generators (DREG) (i.e., solar panels and wind turbines). To accommodate power demands of end users, the 20 kV IEM is equipped with two outputs, including 120 V ac and 380 V dc. 120 V ac is the most common voltage level of power supply for home appliances in North America. Yet 380 V dc is an emerging dc voltage standard [21] dedicated to provide a dc output for data centers [22], uninterruptible power supply (UPS) and lightening applications towards a high energy efficiency.

The "FREEDM community" may run in three different states, including self-sufficiency, charging, and discharging. As DREG and DESD equipments are employed to energize loads in the zone, an equilibrium point can be achieved when powers supplied by DREGs and DESDs are right equal to load consumptions. In that case, Zone A is in a self-sufficiency state and does not need any power from the grid.[3] Accordingly, the charging state means that powers generated or stored in Zone A is not enough to supply its own loads, then energy of the grid will be introduced to supplement the energy shortage. As for the discharging state, it implies that powers inside Zone A are more than enough to supply other zones.

B. Communication Scenarios

Besides critical power electronic equipments, such as IEMs and IFMs, another important feature of FREEDM systems is an efficient communication infrastructure [14], which is responsible for delivering system related messages to confer accurate and timely system awareness to all FREEDM equipments towards efficient and intelligent system managements. For a thorough communication scenario analysis, we divide a FREEDM zone into four levels, including inter-zone level, FREEDM system level, SST level, and user level.

- *Inter-Zone Level.* Communications in the inter-zone level aim to establish connections between multiple power distribution systems for synergetic energy sharing. For example, when Zone A runs in a charging state, i.e. powers of DREGs and DESDs can not satisfy load demands, the zone agent (1 MVA IEM in Zone A) needs to negotiate with neighbor zones to determine which zones it should buy energy from, regarding available powers and real-time prices.
- *FREEDM System Level.* Communications in this level are related to interactions of peer equipments, including the 1 MVA IEMs, five 20 kVA IEMs and multiple IFMs. Towards a well-maintained zone, peer equipments exchange information frequently regarding real-time measures of powers, currents and voltages. Such information exchanges tend to be more frequent in a fault scenario, in which all peer equipments report states in a high rate [15], [23] for a fast and accurate fault positioning.
- *SST Level.* Communications in this level aim to enable the *"dumb"* SST to "talk" with other equipments, including sending out running states, and receiving outside commands for real-time equipment monitoring and control. Thereby, it is more related to on-device communications towards an intelligent equipment.
- *User Level.* The user level involves more equipments, such as loads, DESDs, and DREGs, all of which need to share real-time information for optimized system states. For example, residents can leverage real-time electricity price information to determine how to use excess generated powers, charging DESDs or selling to neighbors.

C. Communication Requirements

According to described communication scenarios, we then summarize potential communication requirements of FREEDM systems in two aspects, including unified data models and categorized performance constraints.

1) Unified Data Model: As a complex system, FREEDM systems integrate diversified equipments, such as IEMs, IFMs, DESDs, and so on. Thus, there is a variety of parameters to be described across distinct equipments, such as current, voltage, and on/off states of circuit breakers. Aiming for coordinated system controls, we should ensure equipments to interpret parameters in the same way. For example, a static binary data is agreed to present the on/off state of a bi-state devices, like a

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[2] A commonly used voltage level in American electric power distribution systems [20].

[3] Note that, although there is no inbound or outbound energy exchange between a self-sufficient Zone A and other zones, energy dispatching still exists inside the Zone A between different 20 kVA IEMs to balance supply/demand relationships among residents.

circuit breaker, whereas a series of *event data* are associated with significant changes on equipments or systems, such as current value exceeding a threshold, or newly available information [24]. Therefore, a unified data model with broad semantic sets is essential as an "official language" to present parameters between FREEDM equipments.

Typically, two data models are widely used in the current power system, i.e., Distributed Network Protocol 3.0 (DNP3) [24] and IEC61850 [15]. The former is the de facto standard in North America for data communications in SCADA systems. The latter is popular in Europe as a promising framework for power data description, which was originally used in substation automation, but is emerging in more smart grid applications, such as demand response and load management [25].

With two dominant data models, we can describe FREEDM data in either way, as long as the following requirements are met. Firstly, the data model needs to cover all data types in FREEDM applications. Secondly, it should present data explicitly and efficiently. Thirdly, the data model should be compatible with two predominant standards, DNP3 and IEC61850, to ensure cost-effective upgrades for off-the-shelf equipments.

2) Communication Performance: Different from conventional communication systems, applications in FREEDM system are mostly mission-critical ones driven by collaborative control tasks of networked equipments. For example, demand response [26] requires to coordinate transformers, loads, and meters to satisfy users' demands on energy quality, whereas relay protection [19] aims to accurately isolate fault feeders by tuning on/off states of interconnected circuit breakers. Hence, communication performance determines the success of such control missions, thereby yielding quite a few of quality of service (QoS) requirements, including available bandwidth, deadline for bulk data traffic, message delivery delay, and so on. Among these QoS requirements, message delivery performance between coordinated equipments is an essential one to ensure timely information exchanges for mission accomplished. For example, in a short circuit scenario, a IFM "Trip" message should be immediately delivered to trigger teleprotection actions for fault isolations in 3 ms [15]. Otherwise, the fault current will damage more equipments in a large area. Therefore, the message delivery delay is an important metric to indicate performance requirements of FREEDM systems, which is formally defined as follows.

Definition 1: The message delivery delay is the elapsing period from the time instant that a message is generated at a source equipment to the time instant that the message is delivered to the destination equipment.

With such a metric, we summarize timing requirements of FREEDM applications [7], [27], [28] as shown in Fig. 3. We can find that delay requirements vary significantly along with applications from several milliseconds to several minutes. The most critical one happens in teleprotections, such as "Trip," "Close," and "Raw Data Sampling" [15]. In contrast, some applications allow a longer delay for operations, up to several minutes, such as feeder reconfigurations and service restorations [7]. Thus, we can conclude that the FREEDM communication infrastructure should follow a delay-oriented design concept to satisfy all timing requirements.

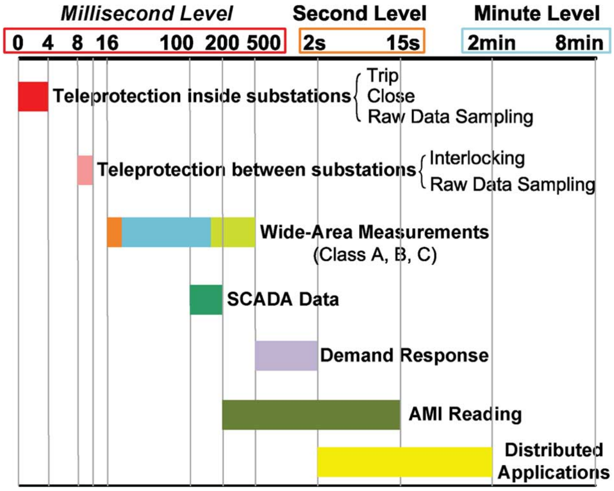

Fig. 3. Timing requirements in FREEDM applications.

D. Summarized Challenges

Therefore, we can summarize that an efficient communication infrastructure of FREEDM systems should possess two features to meet two basic requirements, 1) a unified data model to unambiguously describe system parameters; 2) excellent message delivery performance to satisfy various timing requirements of applications. Accordingly, two fundamental research questions are derived: 1) *how to establish the communication infrastructure to facilitate equipment data exchanges based on unified data representations*; 2) *can established data exchanges satisfy various timing requirements of message deliveries between FREEDM equipments*.

To address these two concerns, we then adopt an empirical approach to practically deploy a DNP3-based communication infrastructure in a small-scale FREEDM demonstration system, Green Hub. Through the prototyped communication system, we intend to investigate the corresponding system performance and identify design spaces of an efficient communication infrastructure in the smart grid.

III. GREEN HUB: A FREEDM SYSTEM DEMO

To acquire first-hand system integration experiences and system performance results, we establish a DNP3-based communication infrastructure to interconnect key FREEDM equipments, including IEMs and IFMs, in a small-scale FREEDM proof-of-concept system, Green Hub. Our objective is to answer the fundamental research question, *how to practically implement and integrate an efficient communication infrastructure with power systems*. To this end, we firstly introduce physical architectures of Green Hub. Then, we present our implementations of a DNP3-based communication infrastructure and corresponding prototyped applications for intelligent power managements.

A. Physical Architecture of Green Hub

The 1 MVA Green Hub system [29], [30] is to demonstrate and verify salient features and capabilities of notional FREEDM systems on renewable energy generation, distribution, storage, and management. The physical architecture of Green Hub is the

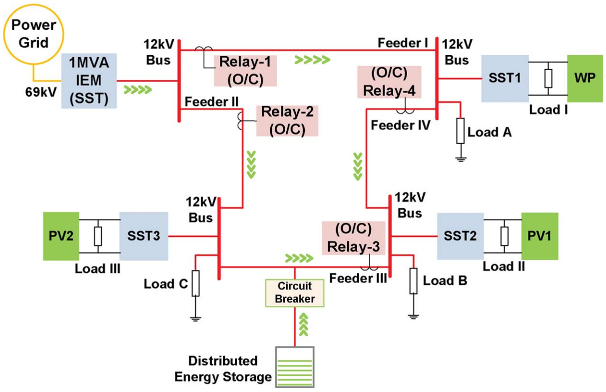

Fig. 4. The physical architecture of Green Hub.

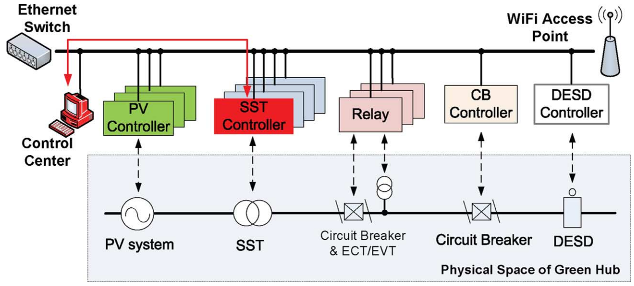

Fig. 5. The communication infrastructure in Green Hub.

instance of Zone A as shown in Fig. 2 by involving three residential houses. One of residential houses is installed with a turbine-based wind power (WP) subsystem, and the other two are with solar-array based photovoltaic (PV) subsystems PV1 and PV2. WP, PV1, and PV2 can generate energy to supply residential Loads I, II, and III, respectively. Also, powers generated by DREGs can be conveyed to the distribution feeder loop via SSTs to energize neighbor houses when necessary, or to supply Loads A, B, and C that are public facilities in the community, like street lights or elevators. In addition, a DESD equipment is placed in Green Hub for energy storage. Users can control the DESD via a circuit breaker (CB) to determine how to use stored energy. For example, when the electricity price is high, users may disconnect DESD to let all excess energy flow to the grid for extra revenue; when the electricity price is low, users may close the CB to involve DESDs to store more but sell less.

Moreover, to ensure the reliability of Green Hub, overcurrent relays (Relays 1, 2, 3, and 4), which are electrically operated switches, are deployed to deal with potential faults on power feeders, such as a short-circuit fault. When the load current exceeds a preset value in some feeders, relays detect abnormal current values via attached Electronic Current Transformer (ECT) and Electronic Voltage Transformer (EVT), and leverage laid communication infrastructures to exchange real-time measures from different observation points, such that they are able to timely identify the fault type, accurately position the fault locations, and synergistically clear the fault with the minimum system costs [31].

B. DNP3-Based Communication Infrastructure of Green Hub

On the basis of the physical architecture of Green Hub, we resort to a DNP3-based communication infrastructure to establish equipment interconnections for real-time information exchanges. In what follows, we firstly present the network architecture of Green Hub, and then introduce the DNP3 over TCP/IP framework and a prototyped DNP3 application used for energy and equipment managements in Green Hub.

1) Network Architecture of Green Hub: Since no default communication interfaces are installed with original FREEDM equipments, to facilitate equipment interconnections, we firstly furnish a microprocessor-based controller[4] [32] with diverse communication adapters (e.g., Ethernet and WiFi) on the power equipment, serving as the interface between a physical power device and the communication network, as shown in Fig. 5. For example, PV systems and SSTs are connected to PV and SST controllers, respectively. Then, all controllers are further connected via an Ethernet switch or a WiFi Access Point (AP) to a 100 Mbps Ethernet based local area network (LAN) or a 54 Mbps 802.11 g based wireless local area network (WLAN), thereby forming a single-hop communication network to connect all Green Hub equipments.

2) DNP3 Over TCP/IP in Green Hub: Only the one-hop network is not enough for bidirectional information exchanges between equipments. We still need a data model to present equipment data as referred in communication requirements. Since the DNP3 over TCP/IP framework has been widely adopted as a communication solution towards the smart grid to achieve good trade-offs between compatibility, efficiency, and simplicity [33]–[35], we employ such a popular framework in Green Hub to "glue" equipment data to the internet protocol suit (TCP/IP) for information disseminations.

Basically, DNP3 is organized into layers as shown in Fig. 6, including user layer, application layer, transport layer and link layer. DNP3 enabled equipments normally work in a master/salve mode, namely, the one that requests data is the DNP3 master, and the other one that responds data is the DNP3 slave. When sending messages, both DNP3 data request or response are firstly generated on the user layer based on data stored in the database [24], such as current and voltage. Then, these data go through different DNP3 layers, and finally are delivered to the destination equipment via TCP streams.

Through such well-defined DNP3 data, users are able to program their own power management applications for specific control missions. In the Green Hub settings, we deploy a prototyped application to achieve real-time monitoring and controls of critical FREEDM equipments. As depicted in Fig. 7, such an application is composed of three modules, including data viewer, command distributor and log collector, which are separately responsible for data display, commands generation and log files recording. A database is developed to store data in types of *Binary, Analog, and Counter*, or commands in types of *Binary and Setpoint* [24].

When queried by other equipments, stored data are pushed down to different DNP3 function blocks, which entails what

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[4] We leave a detailed description of the controller until Section III-C.

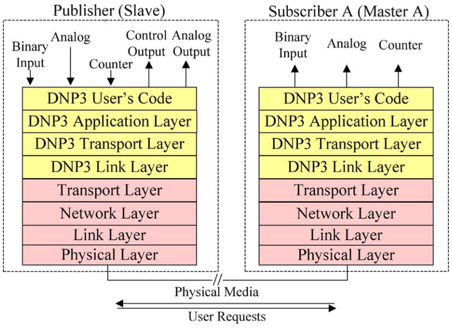

Fig. 6. The protocol architecture of DNP3 over TCP/IP.

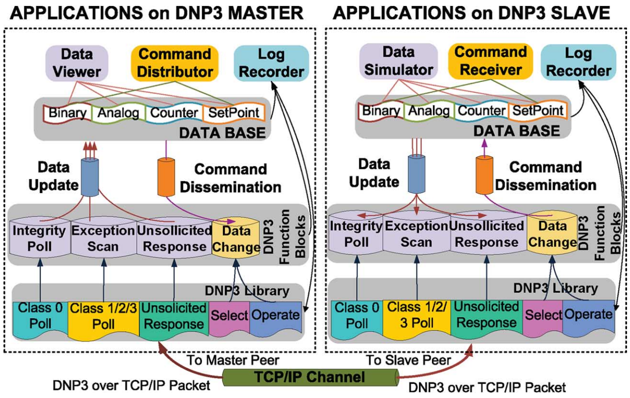

Fig. 7. Applications setup over DNP3-based communication infrastructure.

DNP3 specified operations users want to use to deliver its data. For example, regarding a routine data query, a master equipment may want to issue out data query via the "Integrity Poll" [36] function to acquire all present data on the slave equipment. In that case, data will be pushed into the "Integrity Poll" function block, which further calls underlying "Class 0 Poll" operation according to DNP3 specifications [24], [36] to finish such a routine data query. Generally, four DNP3 functions are aggregated in our applications, including integrity poll (responded by all data on the slave device), exception scan (only responded by changed data), unsolicited response (spontaneously sending data out of the slave device) and data change (changing slave data according to commands), which encapsulate corresponding operations in the underlying DNP3 library [32], [37], such as "Class 0/1/2/3 Poll."

C. Implementations of DNP3-Based Communication Infrastructure

Now we are ready to implement the DNP3-based communication infrastructure in Green Hub for real-time equipment monitoring and controls following the architecture shown in Fig. 5. Since equipments are interconnected as peer links with similar connection methods in Fig. 5, namely, the link between the PV controller and a SST controller is the same with that between a relay and the CB controller, one link implementation can be easily replicated on others for a fully connected system. To highlight implementation details, we take one from multiple peer links, that is, the link between the SST controller and the Control Center marked in red in Fig. 5, to describe the settings.

As shown in Fig. 8, the SST link is composed of two domains: 1) the network domain established by the Ethernet Switch or the WiFi AP; 2) the device domain, which combines two boards as an equipment controller to separate control and communication functions [32] into different boards. We employ a *DSP C6713* board as the control board, running $\mu COS\ II$ operation system to provide a powerful calculation capability for the current/voltage sampling of the SST. In the meanwhile, a *TS-7250* ARM board is deployed as the communication board. The two boards are connected with each other through a RS-232 serial link. A Dell Latitude D820 laptop is used as the control center and equipped with the graphic user interface to show real-time data. We adopt an open source DNP3 over TCP/IP protocol stack [37] to support our monitoring and control applications. Thereby, we establish the DNP3-based communication infrastructure to interconnect Green Hub equipments for information sharing in a real-setting. In the following sections, we will implement various experiments to comprehensively evaluate system performances of such a communication infrastructure.

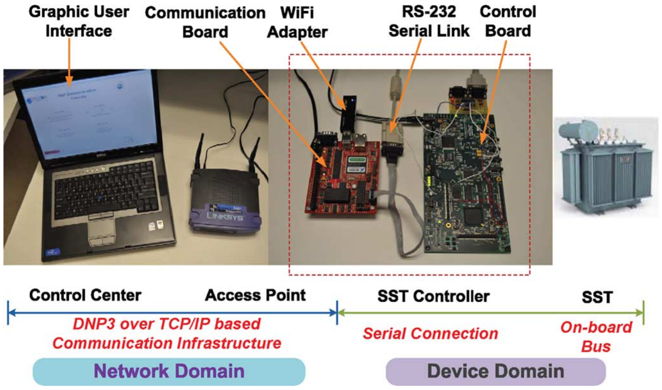

Fig. 8. The hardware and software implementation of Green Hub communications.

IV. Communication Performances of Green Hub

In this section, we illustrate detailed communication performance of the DNP3-based communication infrastructure to address a critical concern, *whether the DNP3 over TCP/IP based communication infrastructure can deliver FREEDM applications messages to meet rigorous timing requirements*. The answer to this question is important for continued studies on communication infrastructures of the smart grid. Firstly, it can help us to clarify the viability of DNP3, the most dominant legacy SCADA protocol used in current North American power systems [24], [34], towards smart grid applications. Secondly, it tends to reveal design bottlenecks of the DNP3 over TCP/IP based communication infrastructure to facilitate possible protocol optimizations, which is significant to cost-efficient retrofits of DNP3-enabled equipments in the smart grid. To this end, we consider a relay protection scenario to resolve message delivery performances of the established communication infrastructure in three steps: 1) we study the diagram of the delivered DNP3 messages in the relay protection use case, and define delay metrics to indicate the communication infrastructure performance; 2) we focus on the DNP3 over TCP/IP framework, the most critical component of the communication infrastructure, to investigate its protocol architecture by means of a thorough baseline performance measurement; 3) we further

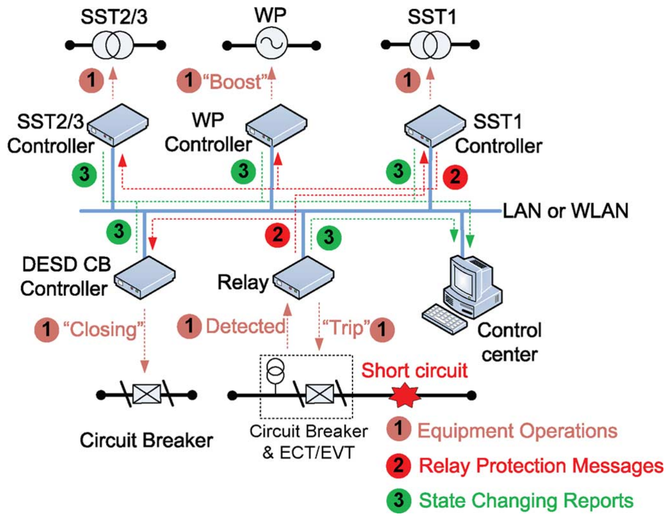

Fig. 9. A relay protection scenario in Green Hub.

study performance of the DNP3 over TCP/IP framework in a real setting test case, in which a variety of routine traffics from different devices are considered. Based on performance results, we present potential performance bottlenecks and discuss possible optimization solutions for both the communication infrastructure and the DNP3 over TCP/IP framework.

A. Experiment Setup

A relay protection scenario consists of the following procedures [38], [39] as shown in Fig. 9: i) When a fault (e.g., a three-phase short circuit) occurs on a power feeder, say Feeder I in Fig. 4, all four relays detect the fault, and Relays 1, 2 and 4 are "tripped" according to preset protection schemes to cut off power feeders, thereby isolating the fault. Accordingly, Green Hub is partitioned into two isolated "islands": Loads I and A are supplied by WP; other loads are supplied by PV1 and PV2. At the same time, two types of messages are shot from "tripped" relays: "closing" commands to the CB controller, and "tripped" reports to the SST1 controller. The "closing" commands intend to connect the DESD system into Green Hub as additional power supply for Loads B and C to prevent them from potential blackout. Three "tripped" relay messages make SST1 be aware of its "islanding" state [40], that means, loads associated with SST1, such as Load I and A, have to be supplied by WP without being connected to the distribution grid. ii) Then, the relays send their reports of the fault and their status changes to the control center. iii) When receiving the (first) "closing" command, the CB controller closes the circuit breaker to connect the DESD system to Green Hub, and then also reports such a "closing" status to the control center. iv) After receiving three "tripped" messages from Relay 1, 2, and 4, SST1 infers that it is in an "islanding" mode, and starts to tune loads and equipments to ensure power supplies, for example, "boosting" WP for more generated power, or resorting to neighbors SST 2 and 3 for possible energy supplies. All these subsequent state changing, such as SST1 "islanding" and WP "boosting," will be reported to the control center, such that the control center may trigger future adjustments to clear faults and retrieve system balances.

TABLE I
LIST OF DEVICE HARDWARE AND SOFTWARE IN EXPERIMENTS

Device	CPU	Memory	Kernel Version
CB Controller	ARM 200MHz	64MB	ARM Linux 2.4.26
Relay	ARM 500MHz	128MB	ARM Linux 2.6.21
WP Controller	ARM 500MHz	128MB	ARM Linux 2.6.21
SST Controller	ARM 500MHz	128MB	ARM Linux 2.6.21
Control Center	P4 1.66GHz	1GB	Linux 2.6.32

As a result, the relay protection requires a series of message exchanges.

1) The "closing" commands (*protection* messages) from relays to the CB controller.
2) The "tripped" reports (*protection* messages) from relays to the SST1 controller.
3) The reports (*real-time monitoring* messages) from relays to the control center.
4) The report (*real-time monitoring* message) from the CB controller to the control center.
5) The "boosting" commands (*protection* messages) from the SST1 controller to the WP controller.
6) The reports (*real-time monitoring* message) from SST1/2/3 and WP to the control center.

All above messages have to been send to expected destination devices before transmission deadlines regarding Fig. 3 to trigger corresponding control operations. For example, the *protection* messages, such as "closing" commands, "tripped" reports, and "boosting" commands, should be received in 10 ms, whereas the *real-time monitoring* messages should be delivered in 100 ms. Otherwise, the DESD system will fail to supply Loads B and C in Fig. 4 to make the public facilities lose power; SST1 will be unaware of its "islanding" mode to lead power shortage happening on Load A and Load I. Thus, the unsatisfactory delay performance finally turns to improper device operations and unsuccessful energy managements to result in multiple blackouts in Green Hub.

We equip the relay and equipment controllers with ARM-based computers, and the control center is a laptop. All parameters of equipments are listed in Table I. Based on such an experiment setup, we then measure deduced message delivery performances in the relay protection scenario.

B. Evaluation I: Performance of the Communication Infrastructure

Towards comprehensive performance understandings, the first questions is *how an equipment signal, such as a fault current, is delivered in a DNP3 message to the control center*. Thus, we take the report message from the relay to the control center as an example to investigate a complete message delivery process in the established communication infrastructure across multiple equipments. Based on the delivery process, we expect to identify critical performance metrics for system performance measurements.

In accordance to DNP3 specifications, DNP3-enabled devices are able to be configured to work in two different modes, including event-driven mode and non-event-driven mode,

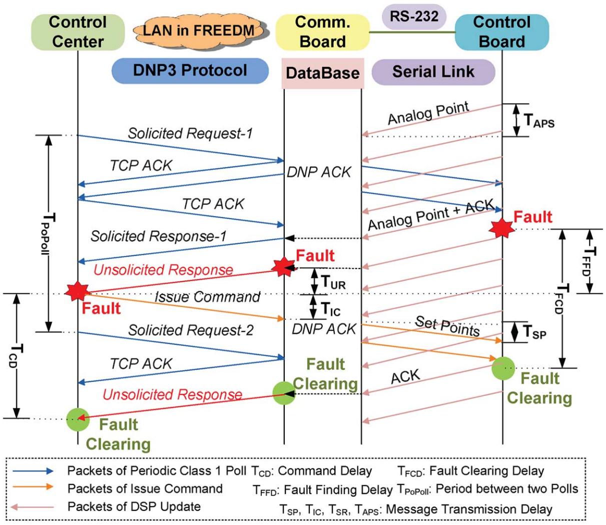

Fig. 10. Message sequence for fault clearing in DNP3 event-driven mode.

TABLE II
DELAY CALCULATIONS FOR FAULT FINDING AND CLEARING IN EVENT-DRIVEN MODE

Delays	Delay Expression
Fault Finding	$T_{FFD} = T_{APS} + T_{UR}$
Fault Clearing	$T_{FCD} = T_{FFD} + T_{IC} + nT_{SP}$
Command Control	$T_{CD} = (T_{FCD} - T_{FFD}) + T_{APS} + T_{UR}$

determined by system requirements and configurations [24], [36]. In the DNP3 event-driven mode, a slave device can spontaneously initiate message transmissions to report its own data change or event occurrence without a specific request. Adversely, in the DNP3 non-event-driven mode, a slave device can not send out a message until a request arrives from the master device. Thus, the deduced message delivery processes are different. Accordingly, we separate performance evaluations in two parts in response to such two DNP3 modes.

1) DNP3 Event-Driven Mode: Fig. 10 shows a fault message delivery process. When a fault happens, it will be firstly observed by the equipment control board through one or multiple out-of-range "analog points," such as abnormal current values on the feeder. Then, the fault information is delivered to the communication board by periodical samplings issued by the control board. Since the communication board is configured on the DNP3 event-driven mode, the arrival fault message will be immediately send back to the control center via a DNP3 unsolicited response message. Based on the fault message, the control center issues several "set points" as the corresponding commands to clear the fault by changing ON/OFF states of associated circuit breakers. When the fault is cleared, the out-of-range "analog points" will fall back into the normal range that will trigger another unsolicited response packet to inform the control center such a new running state. In this process, we are concerned more about three delays, including Fault Finding Delay (FFD), Fault Clearing Delay (FCD), and Command Delay (CD).

According to the message diagram shown in Fig. 10, we summarize the calculations of the three critical delays in Table II. We can see that FFD is mainly determined by the transmission delay of "analog point" sampling T_{APS} on the serial link and the transmission delay of unsolicited response message T_{UR}[5] in the local network; while FCD depends on FFD, the command transmission delay T_{IC} and the delay for those "set points" accepted by the control center nT_{SP}. The command delay relies on both FCD and FFD, and also is affected by transmission delays of sampling and unsolicited response message. Thus, we evaluate FFD, FCD, and CD in the DNP3-based communication infrastructure as shown in Table III. We find that, if the fault occurs at time 0, then it will be observed by the control center at around 11 ms, and cleared at 30 ms. It also takes 30 ms for operators to verify the fault clearing through the updated Unsolicited Response message after commands are issued.

TABLE III
AVERAGE DELAY IN DNP3 EVENT-DRIVEN MODE

Delay	Delay Components		Average Delay (ms)
	Comp.	Comp. Delay (ms)	
FFD	T_{APS}	3.79	11.17
	T_{UR}	7.48	
FCD	T_{FFD}	11.17	30.31
	T_{IC}	0.26	
	T_{SP}	18.97	
CD	T_{FCD}	30.31	30.42
	T_{FFD}	11.17	
	T_{APS}	3.79	
	T_{UR}	7.48	

Compared with timing requirements described in Fig. 3, the Fault Finding Delay, around 11 ms, is much less than 100 ms timing requirements for SCADA data that is most related with equipment monitoring. In terms of FCD and CD, they also show sound performances that can be accepted by equipment monitoring and control related applications in Green Hub.

2) DNP3 Non-Event-Driven Mode: We then analyze the performance of the DNP3 non-event-driven mode. As shown in Fig. 11, a fault signal is still delivered to the communication board via periodical samplings of the control board. Nevertheless, different from the event-driven mode, the communication board can not immediately send the fault back to the control center. Adversely, it needs to hold the fault message until the next arrived data request, called as "polling" in DNP3 [24]. There are several polling types defined in DNP3, we here take the Class 1 poll as the example, as Class 1 poll is defined with the highest priority and only reports data that has changed [36]. When the solicited request message of Class 1 poll arrives on the communication board, the corresponding solicited response message is issued with the fault report. As for the fault clearing process, it is the same as that in the event-driven mode. Only difference is that the fault clearing report is delivered by another solicited response message, not the unsolicited response.

We still take three earlier defined delays as performance metrics, including FFD, FCD, and CD. The delay calculations are presented in Table IV. Since all three delays are determined by the interval between the fault arrival and the first solicited response, the performance of the non-event-driven mode is not a

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[5] Note that we assume that the sampling rate on the control board is high enough in order that the fault can be issued right after its occurrence.

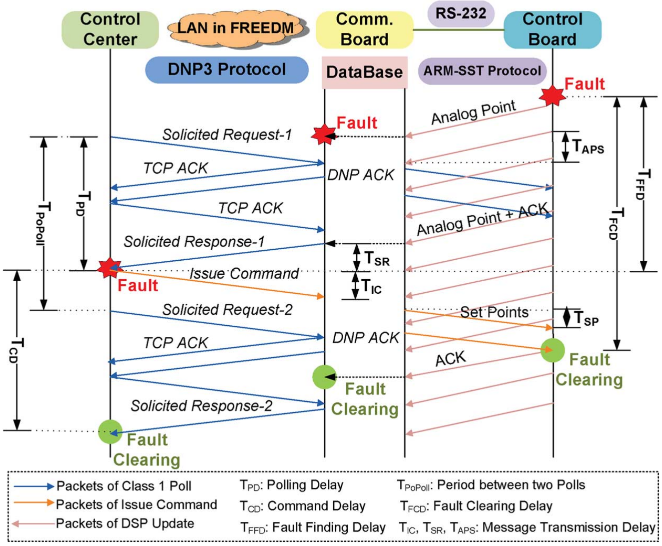

Fig. 11. Message sequence for fault clearing in DNP3 non-event-driven mode.

TABLE IV
DELAY RANGES FOR FAULT FINDING AND CLEARING IN NON-EVENT-DRIVEN MODE

Functions	Delay Ranges (ms)
Fault Finding	$T_{APS} + T_{SR} \sim T_{PoPoll} + T_{APS} + T_{SR}$
Fault Clearing	$T_{FFD} + T_{IC} + nT_{SP}$
Command Control	$T_{Min} \sim T_{Min} + T_{PoPoll}$ [6]

[6] $T_{Min} = (T_{FCD} - T_{FFD}) + T_{APS} + T_{SR}$.

fixed value, but fall in a delay range. In the best case, the fault report arrives right earlier than the solicited response. Then, the fault can be sent back without any delay. In the worst case, the fault report arrives right after the transmission of the previous solicited response, in order that it has to wait for a complete period until the next response message. Therefore, we can conclude that, the performance of the DNP3 non-event-driven mode significantly depends on the frequency of Class 1 poll.

To ensure a shorter delay, the frequency of Class 1 polling should be configured as high as possible to reduce the waiting time. However, a higher polling frequency implies a heavier network traffic on the network, which may result in more congestions or interferences to conversely prolong delays. Therefore, a fine-grained trade-off is an interesting topic between the delay performance and the network traffics [23].

3) Lesson Learned: Through illustrated performance results, we can summarize features of the DNP3-based communication infrastructure in three-fold regarding its applicability, configuration concerns, and potential performance bottlenecks.

First, on the basis of the 11 ms fault finding delay, the DNP3-based communication infrastructure is able to provide message delivery services for most popular power management applications with satisfactory delay performance in FREEDM systems, such as wide-area measurements and demand response.

Second, despite the fact that the communication infrastructure shows a broad applicability towards FREEDM applications, a fine-grained system configuration is essential based on a comprehensive system understanding to achieve such a broad applicability in a real-setting deployment. Any inappropriate configuration may result in unexpected performance deteriorations for message deliveries, thereby missing transmission deadlines and failing control missions. A typical example is the operation mode configuration of DNP3-enabled equipments. Due to significant performance differences between two DNP3 modes, oblivious configuration errors may paralyze applications by disabling the efficient message delivery mode.

Thirdly, through the message diagram, we can find that, the message delivery delay is composed of many "delay ingredients," including network transmission delay, on-board processing delay, even transmission delays between two boards inside the equipment controller, like T_{APS} and T_{SP} in Table III. Such "delay ingredients" originate from three timing-consuming processes, including message transmissions across the network, the DNP3 over TCP/IP protocol stack processing and data transmissions deduced by the dual-board architecture of the equipment controller.

- Delays of message transmissions over the network are mainly determined by the network size, that is, the larger geographical area a network covers, the longer cables and the more network devices are needed, accordingly, the longer delay we will achieve when transmitting messages through the network. Thus, message transmission is a non-negligible factor to impact the delay performance in long-distanced connections, which usually happens in the power transmission network. Yet, in our case, FREEDM systems focus more on the power distribution network, especially in the residential community with geographically-close neighbors, in which the distances between interconnected power devices are limited in tens of meters. Correspondingly, the delay impact of message transmissions is not as significant as that in the long-distanced power transmission network, and is negligible compared with the other two "delay ingredients."
- As a key "delay ingredient," the on-board processing delay will be detailed analyzed in the following sections.
- The last "delay ingredient" is more related to transmissions on the serial link inside the controller. Based on Table III, 3.79 ms T_{APS} and 18.97 ms T_{SP} contribute substantial proportions on final delay results, such as 34% in the fault finding and 75% in the fault clearing. Therefore, we can conclude that, the RS-232 link is not an optimal design to connect the control board with the communication board, as considerable delays are derived on the inefficient serial link. An alternative way is to replace the slower one with a high-speed data bus, such as Ethernet or USB, to achieve notable improvements on delay performance.

C. Evaluation II: Baseline Performance of the DNP3 Over TCP/IP Framework

Besides transmissions of the serial link inside the equipment controller, another time-consuming process in a complete message delivery diagram is the processing of the DNP3 over TCP/IP framework, which undertakes responsibilities of data packaging and DNP3 message transmissions, measured by

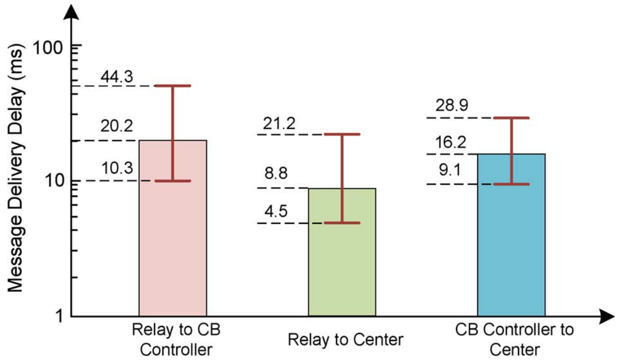

Fig. 12. The message delivery delay performance for different messages in DNP3 over TCP/IP.

T_{UR}[6] in Table III. Moreover, we notice that 66% of the fault finding delay is contributed by 7.48 ms T_{UR}. It entails that, in comparison with transmissions on the serial link, the DNP3 over TCP/IP protocol stack processing is the dominant factor to influence message delivery performance regarding timing requirements shown in Fig. 3. In that case, we then leverage the DNP3 unsolicited response message to analyze impacts of the DNP3 over TCP/IP framework on the message delivery performance in Green Hub.

According to the aforementioned relay protection scenario, there are a series of messages to be exchanged between equipments after a fault happens, such as "tripped" reports from relays to the SST controller and "boosting" commands from the SST controller to the WP controller. In the following experiments, we choose three messages to simplify experiments: i) "closing" command from the relay to the CB controller, ii) state change report from the relay to the control center, and iii) state change report from the CB controller to control center. As we adopt the same ARM boards in Relay, WP controller, and SST controller, as listed in Table I, performances of untouched messages are prone to be reflected in the three example messages. Then, we present measurement results of DNP3 messages in Green Hub.

1) Performance Results: Fig. 12 shows the delivery delay performance (with mean, maximum, and minimum) of the three messages. Note that, if an equipment is configured to monitor another equipment, such as the CB controller monitoring the relay, or the control center monitoring the CB controller, both equipments maintain an active TCP connection by periodically issuing data polling [24]. Thus, when transmitting the "closing" command and state change reports, two equipments don't need the time-consuming 3-way handshake to establish a new TCP connection. Therefore, we can see that the average delivery delay varies significantly, even though all devices are in the same network. The best performance is achieved by the state report from the relay to the control center whose average delivery delay is lower than 10 ms. In contrast, the average delay between the CB controller and the center is 16.2 ms with the maximum delay at nearly 29 ms. The worst performance appears on the path between the relay and the CB controller, where the average value is over 20 ms.

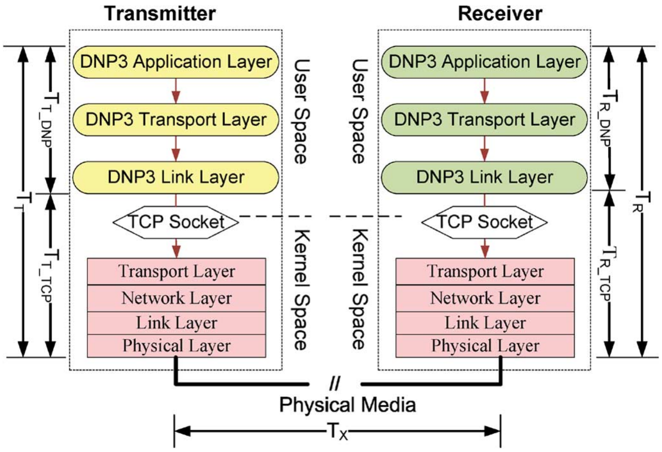

Fig. 13. Delay components in the DNP3 message processing.

TABLE V
TRANSMITTING AND RECEIVING PROCESSING DELAY IN DIFFERENT DEVICES

Device	Transmission (ms)		Receiving (ms)	
	T_{T_DNP}	T_{T_TCP}	T_{R_DNP}	T_{R_TCP}
Relay	11.856	3.087	10.828	1.871
CB Controller	6.088	1.395	5.829	0.847
Center	0.501	0.357	0.489	0.271

2) Performance Analysis: In this experiment, we measure the delay performance of three messages delivered in a sequential manner in the same 100 Mbps Ethernet-based network, but obtain evidently different performance results. This indicates that the processing time at protocol stacks in embedded computers plays an important role in the delay performance, since the relay and CB controller are both equipped with embedded computers.

To further explore the effect of processing time, we take a close look at the entire delivery process of a DNP3 unsolicited response message. Fig. 13 illustrates all delay components in an unsolicited message delivery, including the transmitter's processing delay T_T, the network transmission delay T_X, and the receiver's processing delay T_R. T_X is a constant since all messages have the same length during experiments. Yet, the processing delays, T_T and T_R, may vary significantly with different devices. Thus, we divided T_T or T_R further into two parts: the DNP3 processing delay and the TCP/IP processing delay. Namely, $T_T = T_{T\_DNP} + T_{T\_TCP}$ and $T_R = T_{R\_DNP} + T_{R\_TCP}$. Table V shows mean values of all delay components in different devices.

It is evident that DNP3 over TCP/IP can lead to distinct processing delay performances with different computational capabilities. According to Tables I and V, the control center performs best due to its high-speed CPU. Whereas, the two embedded computers, the CB controller and the relay, both suffer from worse processing delay performance because of limited CPU speeds. Since a large amount of smart grid devices are only equipped with embedded computers, we conclude that the processing delay is a non-negligible factor in the delay performance in the smart grid.

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[6] Since DNP3 event-driven mode is much more efficient than the non-event driven mode, in what follows, we assume that all DNP3-enabled equipments are configured in the event-driven mode, and then we mainly focus on the analysis of DNP3 unsolicited response messages.

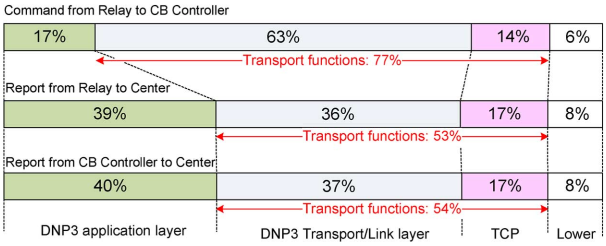

Fig. 14. Ratios of all delay components in the message delivery delay.

Note from Table V that DNP3 results in more processing delay than TCP, which is more obvious in embedded equipments. For example, compared with only 3 ms processing delay for TCP transmission on the relay, the processing delay of DNP3 transmissions is even over 11 ms. Such an observation implies that the protocol efficiency is another factor that can dramatically influence overall delay performance. To investigate the impact of protocol efficiency, we further break down message delivery delays into four components: DNP3 application-layer delay, DNP3 transport/link-layer delay, TCP-layer delay, and lower-layer delay. We show the ratio of each delay component to overall message delivery delays in Fig. 14.

From Fig. 14, we can observe that the delay induced by mechanisms for reliable transport, including DNP3 transport/link layers and TCP, is the most dominant delay component in the overall delay performance. However, reliability mechanisms in DNP3 and TCP are in fact similar to each other. As originally designed over serial links that provide little reliability, DNP3 has its own transport and link layers to achieve reliability mechanisms, such as connection confirmation, cyclic redundancy check, and retransmission mechanism [24]. Similarly, TCP also provides reliability for message delivery. In other words, our results show that such an overlapped design in DNP3 over TCP/IP in fact induces 50%–80% of the overall processing delay in embedded computer based power devices, as shown in Fig. 14.

3) Lesson Learned: When comparing Fig. 12 with timing requirements in Fig. 3, we can achieve contradictory, yet interesting conclusions regarding the feasibility of DNP3 over TCP/IP in the smart grid. On the one hand, since the average delay for status reporting ranges from 8 ms to 16 ms, much less than the 100 ms timing requirement for SCADA data, DNP3 over TCP/IP is qualified for *real-time monitoring* and *low-speed* applications. On the other hand, as the "closing" command belongs to *protection* messages whose timing requirement is smaller than 16 ms, the 20.2 ms average delivery delay of the "closing" command results in that DNP3 over TCP/IP can not be reliably used to deliver time-critical messages in teleprotection related applications, although it is widely considered as a simple and compatible solution in the smart grid [34].

To accommodate DNP3 over TCP/IP to time-critical applications, two solutions are feasible by improving the processing efficiency of the DNP3 over TCP/IP message. The first is to upgrade the hardware of embedded power control devices with more computational capabilities, which can obviously improve the delay performance by reducing the processing delay. However, this inevitably increases the cost of smart grid devices. The second solution is to optimize the DNP3 over TCP/IP framework, as we have already identified that the overlapped reliability design in DNP3 and TCP causes redundant processing delays, as shown in Fig. 14. An intuitive way to fix this problem is to exploit more efficient UDP/IP to replace the original TCP/IP towards a DNP3 over UDP/IP framework, where the transmission reliability is only undertaken by DNP3. If this idea works, we can only upgrade softwares of deployed DNP3 equipments without retrofitting them. Yet, before that, we need to understand delay performances of DNP3 over UDP/IP in the same scenario.

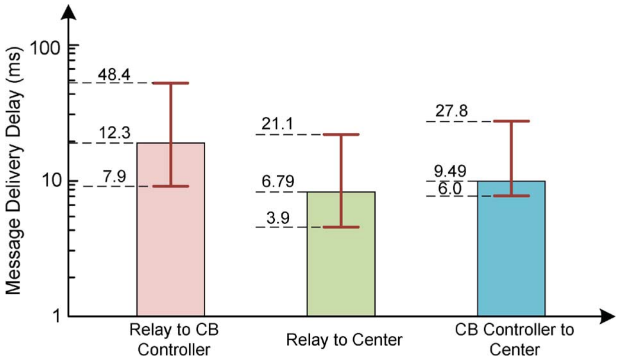

Fig. 15. The message delivery delay performance for different messages in DNP3 over UDP/IP.

Fig. 15 shows the performance of DNP3 over UDP/IP; we find that performance gains in DNP3 over UDP/IP are significant in relation to Fig. 12, since UDP messages are much lighter than TCP ones in processing. Nevertheless, it is still unqualified for teleprotection applications in all trials regarding rigorous timing requirements. The reason lies in that, the multi-layer design of DNP3 is so complicated and processing-heavy that processing delays between DNP3 layers remain inevitable.

Then, we can summarize that the DNP3-based communication infrastructure is viable for most applications in Green Hub, including equipment monitoring, AMI reading, demand response, and so on. In other words, although DNP3 has already served us for decades of years as a legacy protocol, it can still catch up with the smart grid vision in many applications, which entails that, the ongoing evolution of power systems towards the smart grid can be cost-efficient if most deployed DNP3-compatible devices can be retained and fully utilized. Nevertheless, as DNP3 is not an efficient solution, no matter which underlying protocol is adopted, TCP/IP or UDP/IP, the resulting communication infrastructure is not suitable for time-critical applications, such as teleprotections, whose timing requirements are limited in 10 ms. Therefore, we may need another efficient protocol dedicated for those time-critical applications in Green Hub.

The conclusion also agrees with our observation, that is, there exists a mismatch between timing requirements and the practical delay performance. On the one hand, timing requirements of FREEDM systems feature multiple delay levels ranging from milliseconds to minutes in Fig. 3; on the other hand, delay performance of DNP3 delivered messages fluctuates from several milliseconds to tens of milliseconds regarding the computation capability. Thus, another interesting question is derived, that is, *how to design a communication protocol to accommodate multiple levels of delay performance.*

Based on our knowledge, a single protocol with the limited adaptability seems to be hard to satisfy so various delay demands. Taking DNP3 as an example, as aforementioned, DNP3 is not suitable for time-critical applications due to the complicated protocol architecture, and another dedicated protocol is urgently needed as a supplement. Therefore, a comprehensive communication profile, not a single protocol, may be a better solution by combining multiple protocols to deal with different applications that require distinct timing requirements for message deliveries. The concept of the communication profile is also adopted by IEC61850 [15], [41], another popular communication standard in the smart grid, which involves 5 protocols serving for different kinds of message deliveries, including sampled measurement values, fast transmitted substation events, time synchronization, and so on. Among these protocols, each protocol holds special designs to accommodate specified applications, such as lightweight protocol processing for fast transmitted substation events, and TCP-based reliable message delivery for control commands [41]. Following the same way, we can extend the current DNP3 over TCP/IP framework to involve a more efficient protocol for time-critical messages by further simplifying the protocol architecture, thereby achieving a DNP3-based communication profile to cover all delay demands. That is, time-critical messages are transmitted by the dedicated protocol, the other messages are transmitted through the DNP3 over TCP/IP framework according to transmission priorities determined by timing requirements.

D. Evaluation III: Practical Performance of the DNP3 Over TCP/IP Framework in Green Hub

In previous experiments, we have measured the baseline delay performance for message exchanges between the relay, the CB controller, and the control center, which clearly reveals performance impacts of the DNP3 over TCP/IP framework on message deliveries. However, these baseline delay results, as shown in Fig. 12, are not the practical performance we can achieve in a real-setting Green Hub, as they are evaluated without considerations of background traffics from other devices. Towards a comprehensive performance understanding of the DNP3 over TCP/IP framework, in this experiment, we consider the same relay protection scenario as shown in Fig. 9, but measure the delay performance with all devices connected in the network, as shown in Fig. 5.

1) Traffic Load: Before presenting our experimental results, we first briefly describe the traffic load in Green Hub. In the normal state, all device controllers are set to periodically transmit their running states to the control center with an aggregated traffic rate at 600 kbps. During the course of fault managements, controllers that detect abnormal states, like relays and SST controllers, are set to report faults to the control center for centralized managements. To ensure a timely and accurate monitoring of fault changes at the control center, all device controllers are required to transmit real-time measurements to the control center at the rate of 4800 messages per second [15], [42]. Each message includes an instant sample of power signals, including voltage and current readings. After the fault management, the control center will send commands to devices to resume the normal state.

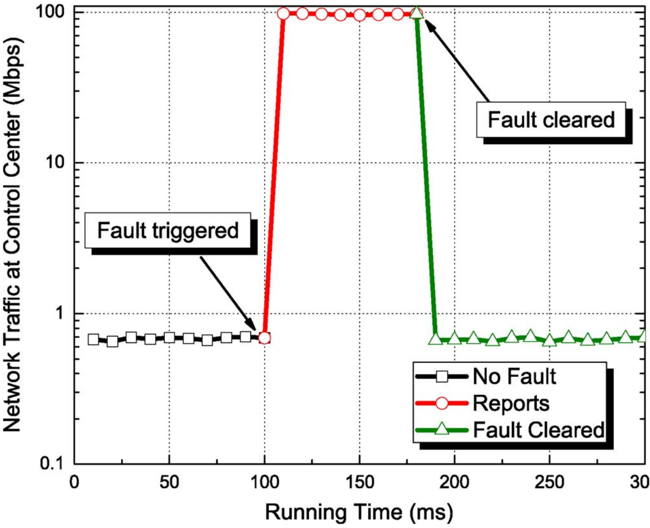

Fig. 16. Network traffic loads at the Control Center.

2) Experimental Result: Then, we trigger a fault on Feeder I (as shown in Fig. 4) to initiate the same relay protection procedure used in baseline performance measurement. Fig. 16 illustrates the traffic dynamics at the control center. The traffic is 600 Kbps initially, which is mainly composed of various routine polling traffics used by the control center to query device states. When the fault occurs, the traffic dramatically increases to nearly 100 Mbps. This is because, after the fault happens, all device controllers, including the relays, SST controllers, and PV controllers, will simultaneously detect the anomalies due to the physical correlation between power equipments in Green Hub. Furthermore, in accordance with preset fault reporting requirements, all devices attempt to send abnormal data to the control center, thereby leading to a saturated network traffic load at the control center.

With such traffic dynamics, we measure the delay performance of message exchanges in the same relay protection scenario. The results are illustrated in Fig. 17. Comparing Fig. 12 with Fig. 17, we find that the “closing” command from relays to the CB controller remains approximately the same; however, the delay performances of the other two messages are slightly degraded due to the saturated traffic load at the control center. For example, the mean delay from the relay to the control center increases from 8.8 ms to 12.6 ms, and the mean delay from the CB controller to the control center goes from 16.2 ms to 19.9 ms. We can conclude that, in the case of fault management, the delay performance of *real-time monitoring* messages delivered to the control center can be degraded due to a traffic flooding effect. However, the experimental results show that DNP3 over TCP/IP is still suitable for *real-time monitoring* in Green Hub.

3) Lesson Learned: Our experimental results indicate that, although the achievable delay performance is deteriorated by the traffic flooding effect during the fault clearing, DNP3 over TCP/IP framework is still viable for *real-time monitoring* applications in accordance with Fig. 3. It is worth mentioning that, the network traffic load and performance are indeed coupled with physical architectures in the smart grid. For example, when a

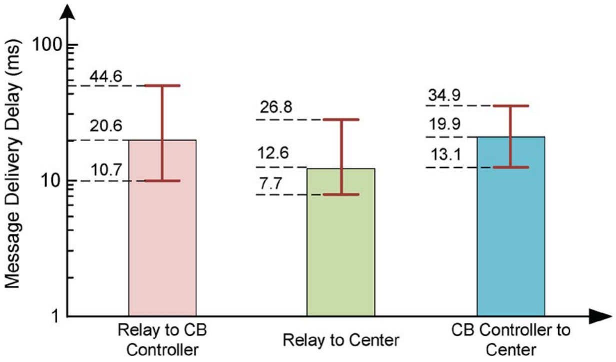

Fig. 17. The message delivery delay performance for different messages in Green Hub.

short circuit happens on Feeder I in Green Hub, all relays and related devices can detect the fault by observing a current increase due to the correlation between physical feeders. Accordingly, the event of the electric distribution network can trigger a series of message deliveries between multiple power devices, and further may lead to a traffic flooding phenomenon as shown in Fig. 16, which should be taken into consideration seriously in the communication system design of the smart grid.

In addition, our experimental results indicate that DNP3 over TCP/IP can be still used for *real-time monitoring* in Green Hub. On the other hand, we observe that smart grid fault management requires a large amount of information exchanges, which can in turn degrade the delay performance of message delivery, especially in large-scale smart grid networks. In this regard, DNP3 over TCP/IP for the smart grid can be further designed to assign priorities to different messages with distinct delay requirements. For example, *protection* messages must have the highest priority; and *real-time* messages should have a higher priority than *low-speed* messages.

V. CONCLUSION AND FUTURE WORK

In this paper, we reviewed designs and implementations of the communication infrastructure serving for equipment interconnections in envisioned FREEDM systems towards bidirectional energy and communication flows. To achieve an efficient and practical design, we started from a well-rounded investigation of FREEDM system architectures, aiming to identify communication requirements and useful use cases. On the basis of a comprehensive system understanding, we focused on the design of a full-fledged communication infrastructure by adopting the widely used DNP3 over TCP/IP framework to establish interconnections between critical FREEDM equipments in some typical system use cases.

To verify the feasibility of the DNP3-based communication infrastructure regarding various communication requirements, we developed a system platform in a real setting to interconnect diversified FREEDM equipments and evaluated the corresponding system performance of the established communication infrastructure. Through the system implementation and performance evaluations, we acquired first-hand experiences and performance results with respect to the communication infrastructure in the smart grid, which is not only applicable for FREEDM systems, but valuable for other similar systems toward the smart grid. In the future, we will make more efforts on a completed communication solution to reach more related fields, including security issues and system reliability issues, to establish a reliable and secure communication infrastructure for FREEDM systems.

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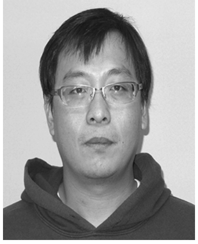

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