ORIGINAL ARTICLE

Communication Network for Smart Microgrid

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Abstract: This paper conveys development, validation and performance analysis of a communication network for facilitating bi-directional communication in a microgrid adhering to smart grid communication standards. The work encompasses proposing a suitable topology for the communication network and communication technology selection from among technologies like IEEE 802.3, 802.11, 802.15.4 for data transfer by performing communication network simulation in Netsim, a network simulation software. The simulation in Netsim delivers the performance of communication network for various technologies through performance indices like throughput, packet delivery ratio, round trip delay, collisions, protocol overhead time, network setup time etc. Netsim simulation of the heterogeneous communication network, selected from analysis of communication network simulation using multiple technologies, enables its performance validation. This work renders better comprehension in realization of Wide Area Measurement System for real time data collection and status update, Wide Area Control Systems for real time control and Advanced Metering Infrastructure for user integration transforming a microgrid to a smart microgrid.

Keywords: Communication Network; Smart Grid Simulator; Smart microgrid; WACS; WAMS

Introduction

Smart grid signifies an evolved power system that has intelligent and innovative technologies for real time and bi-directional information and power flow over the entire network spanning from generation to end use points [1]. The enormous amount of diverse data that various smart devices distributed throughout the grid generate, must reach control devices and intelligent energy management systems at various levels [2]. This is conceivable only with the help of a proficient, reliable and secure communication network interconnecting various distributed metering, monitoring, control and data transfer devices in smart grid. This communication network must sanction bi-directional movement of data for real time updation of grid status and control of operations.

Microgrid is a scaled down version of the full-sized power system network that contains all modules and permits all operations of the latter [3]. Therefore, like the smart electrical grid, the microgrid needs a communication network to transform it into smart microgrid. The microgrid communication network has more stringent demands, sometimes, than that of a conventional grid as the microgrid operation involves both grid connected and islanded modes. In addition to the message passing required for regular operational activities, the microgrid communication network will need to help realize message passing for a variety of demand side applications such as demand response, time of day tariff, distributed generation, etc. [4].

However, the realization of such systems directly on field takes long hours of planning. Laboratory simulators or emulators can play a vital role in such situations in carrying out hardware realization and validation of most concepts. The five-bus microgrid simulator in [5] is one such laboratory simulator that helps to implement and validate distribution side operations and applications. A lot of work is in progress globally in development of laboratory scale simulators that help in validation of emerging concepts and their applications in smart grid or smart microgrid [6]. The use and the merits of simulators in validating various smart grid operations and schemes have been presented in [7].

This paper details the design and development of a bi-directional communication network for the microgrid referred to in [5], to convert it to a smart microgrid. Contemplating the operational needs as monitoring, control and specific end use applications, the communication network topology has been designed. Simulation of the communication network in Netsim, the communication network simulator tool, using communication technologies like IEEE 802.3 (wired Local Area Network (LAN)), 802.11 (wireless LAN), 802.15.4 (Wireless Personal Area Network (WPAN)), etc. aided in identifying and evaluating the performance indices of all these technologies for smart message passing in multiple smart microgrid services. The validation, in Netsim, of the heterogeneous network, conceived with the technologies selected based on the simulation results, substantiated the network performance in data communication.

Section II outlines the communication requirements, technologies standards and simulators in the field of smart grid. Section III presents the microgrid under consideration and the methodology for developing the communication network on this microgrid. Section IV serves the topology and technology selection. Section V deals with choice of heterogeneous network and evaluation of its performance; section VI concludes the paper.

Background Study

Automation of power system, especially the power distribution system, suggests incorporating a number of smart devices in a distributed fashion for monitoring, control and consumer side applications. Such nodes generate a large amount of data related to generation, transmission and distribution, operation, consumption and billing information which has to be handled in real time. Data handling includes communication and storage of data in addition to processing and decision making which happen at various levels of hierarchy.

Power system, conventionally, is divided into four sectors viz., generation, transmission, distribution and end use, and each of these sectors has different requirements as far as the communication needs are concerned [8]. Traditional centralised generation plants employ Supervisory Control and Data Acquisition System (SCADA) based systems for automation and this involves data communication between RTUs and SCADA master and message passing to the control centres. One aspect of communication in transmission sector includes collecting data from the large number of distributed Phasor Measurement Units (PMU) and passing it up to control centres in the hierarchical network through Phasor Data Concentrators (PDC) and Super PDCs in a deterministic manner. The second aspect involves message passing for control actions initiated from control centres or operational centres at various hierarchical levels to control units placed at different transmission sub stations [8].

The communication requirements of the power distribution sector are all the more complex and different as distribution sector incorporates distributed generation with energy storage, power flow from these to different types of consumers and even dispatchable loads [9]. Recent concepts of power distribution grid suggest transformation of the conventional distribution network to interconnected microgrids which possess all operational and functional qualities of a power grid [9] [10]. This implies that the communication network for a smart distribution grid or a smart microgrid has to meet all the requirements of generation and transmission sectors and address in addition, specific communication requirements. These include grid interconnection, microgrid islanding and consumer side applications like Demand Response (DR), load scheduling, Advanced Metering Infrastructure (AMI), etc. [8].

There are various standards that govern data exchange in smart grid applications in terms of message sequences, data frame formats, timing requirements, data content and relevant rules. IEEE C37.18.2 [11] prescribes the data exchange standards for PMU applicable for message passing in Wide Area Measurement System (WAMS). These standards are particularly defined for the operations in transmission sector of the electrical power system. IEC 61850 deals with substation automation and inter substation communication. IEEE 1815 - 2012 (Distributed Network Protocol (DNP3)) specifies message passing for communication to provision control actions at various levels of smart grid operation [12]. IEC 62056

(Device Language Message Specification – Companion Specification for Energy Metering (DLMS-COSEM)) is a set of standards that govern the message passing for energy meter for conventional metering and AMI applications [13].

Of these standards for smart grid, the ones for generation and transmission sectors have undergone a fair amount of evolution. For a good range of applications in the distribution and end use sectors the standards are still at a nascent stage, whereas the standards are yet to come for a bigger number of applications. As a large number of applications and services exist in the same geographical region, the distribution grid or microgrid communication puts forth interoperability of services and coexistence of technologies as two important parameters of Quality of Service (QoS) [14]. This is particularly important as microgrid communication can explore the possibility of data exchange over a wide variety of communication technologies like IEEE 802.15.4, 802.3, 802.11, IoT protocols, etc. unlike other power system sectors because of the close proximity of nodes in the microgrids [15].

Researchers around the globe are seriously involved in developing and using simulators for smart grid research. These simulators include software, hardware and combined hardware-software platforms [16]. Software simulators that address generic smart grid problems are normally developed following mathematical modelling of power system with integrated communication network simulation tools too. The entire power and associated ICT system will be developed in different but linked software platforms. The hardware-only simulators are usually laboratory systems which are scaled down models of real field power system networks and are intended to test and develop solutions for specific problems. The hardware-software simulators are Hardware-In-Loop (HIL) systems that help to model and study problems related to power system, control system and communication system and try out possible solutions without the trouble and risk of testing in real field systems while at the same time providing more realistic operational environment [16] [17].

Many research labs and universities have HIL systems which can mimic all operations of smart grids and can act as test beds for all sub systems aiding in smart grid realization. A hardware simulator for a DC microgrid, having various distributed sources, storage options and Controller Area Network (CAN) as the communication system facilitating power management, state monitoring, and performance analysis is described in [18]. A real time power system test bed enabling operation, control and cyber security features is presented in [19]. This test bed has Real Time Digital Simulator (RTDS), various power system control devices and server and data storage facilities with Human Machine Interface (HMI) for monitoring, control, data analytics and cyber vulnerability studies. National laboratory of smart grid (LAB+i) at National University of Colombia - Bogota Campus, which serves as a test bed for measurement, control and communication technologies in smart grid domain is brought out in [20]. This test platform provides a facility for various studies including optimization of control logic, adaptive technology testing, and, assessment of operational situations and needs. A real time end to end smart grid cyber physical test facility, with RTDS and ns-3 provisioning PMU, PDC interface and modeled communication, for studies on cyber security and its impact on power system network is presented in [21]. Various microgrid test beds around the world, its features, facilities, development and use-cases are detailed out in a broad fashion in [22].

Smart microgrids are cyber-physical systems that demands optimal performance of the cyber system for the efficient operation of the physical system. HIL systems are perfect tools that can be used for research and experimental studies on such cyber-physical systems. Such a scaled down microgrid simulator is presented in [5] which can be used as a test bed for smart distribution grid studies. This microgrid uses Real Time Data Collection Units (RTDCU) and it has basic communication network for data exchange between RTDCU and server [23]. Authors of [24] proposed a heterogeneous network for realizing WAMS capability whereas another heterogeneous network for realizing Wide Area Control System (WACS) capability is proposed in [25]. Further, [26] proposes a communication network for message passing from Smart Meters (SM) in consumer premises considering multiple topologies of smart meter network. The present work proposes a comprehensive and heterogeneous bi-directional communication network that addresses communication requirements of the WAMS, WACS and AMI systems for the 5-bus microgrid.

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System Overview and Methodology

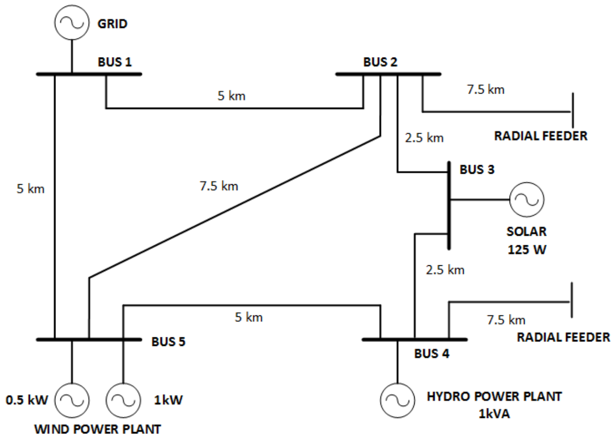

Figure 1. Single Line diagram of 5-bus microgrid [5]

The microgrid under consideration has five buses with grid connection at bus 1, PV power plant and battery at bus 3, micro hydel generator and pumped hydro storage at bus 4, wind electric generators at bus 5, and, radial feeders provided at bus 2 and 4 to connect to loads, as shown in Figure 1. The RTDCU present in the microgrid make real time measurements of voltage and current, then compute frequency and phase angle, and, initiate data flow on WAMS network. The control units help realizing WACS network by connecting or disconnecting source/storage/feeders based on messages received from the control centres. The smart energy meters distributed on the radial feeders do energy measurement and load control based on messages from the control centres and thus realize AMI network. The bi-directional communication network proposed in this paper targets to achieve both Wide Area Measurement Protection and Control (WAMPAC) and AMI capabilities for the microgrid shown in Figure 1.

The first task in developing the communication network is to consider the positioning of member nodes and define the topology of the network maintaining the hierarchy needed for the data flow. Adoption of the appropriate data communication standards, the format required for data communication, the request-reply sequences required to be maintained for message exchange corresponding to various operations and the listing of *who should talk to whom,* form the second step. The third job in the process is to assimilate the data exchange requirements. The next activity is to select the communication technology that will realize the physical data transfer by enabling connectivity among the member nodes following the topology definition and satisfying the communication requirements. This can be achieved by simulation of the communication network in a suitable software following the required standards. The simulation also helps in performance analysis of the communication network itself with the technology under consideration. The performance of the communication network can be analysed based on various performance indices like throughput, packet delivery ratio, round trip delay, network setup time, number of intermediate nodes, etc. Communication network simulators like NetSim, ns2, ns3, OMNeT++, Opnet, etc. can help in the selection of communication technology and performance evaluation of the communication network.

System Design and Implementation

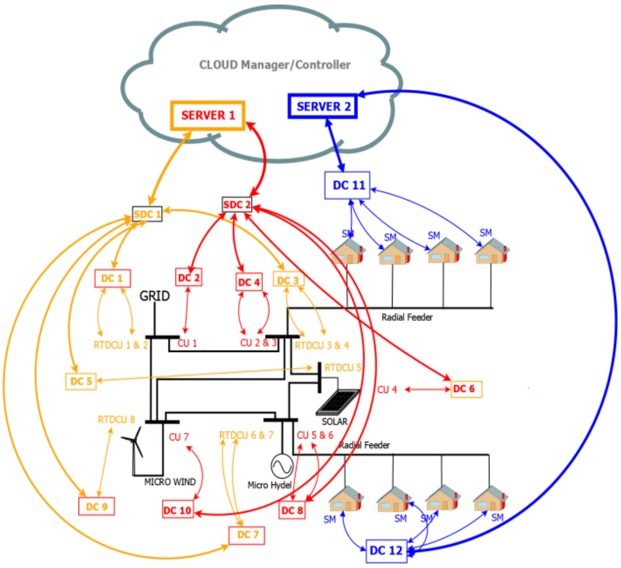

Figure 2. Layered Communication Architecture for the 5-bus microgrid

The network intends to pass messages for three different services viz. real time monitoring, control and smart metering. The real time monitoring message passing network has RTDCU and Data Concentrator (DC) for each bus and server for data communication. The communication network for control message passing has control units and DC for each bus and server. The smart meter network has smart meter associated with each consumer and DC to collect data from multiple smart meters and server to realize AMI network. The proposed communication network follows a hierarchical structure with the measurement and control nodes forming the end nodes, and, servers acting as control centres forming the top most nodes. The intermediate layers are occupied by different levels of DC. Figure 2 shows the hierarchical structure of the layered communication architecture for the 5 bus microgrid.

The microgrid communication network has four functional layers for all the three identified services satisfying respective standards. Addition of WAMS capability is achieved in this network by following IEEE C37.118.2 standard for data exchange among RTDCU, DC and server. This network mimics the PMU-PDC-Control Centre network, accomplishing WAMS in microgrid. Similarly control on grid operation for the entire microgrid is brought in through message exchange following IEEE 1815-2012 standard. This network mimics the DNP3 based message passing for power system control, achieving WACS for microgrid. Consumer integration to grid is one of the most promising feature that the smart grid evolution has brought forward and microgrid or distribution grid is the functional sector of a power grid that has to realize this feature. This is achieved through messages following IEC 62056 (DLMS-COSEM) standard from smart meter nodes effecting AMI network attaining metering and other consumer side applications.

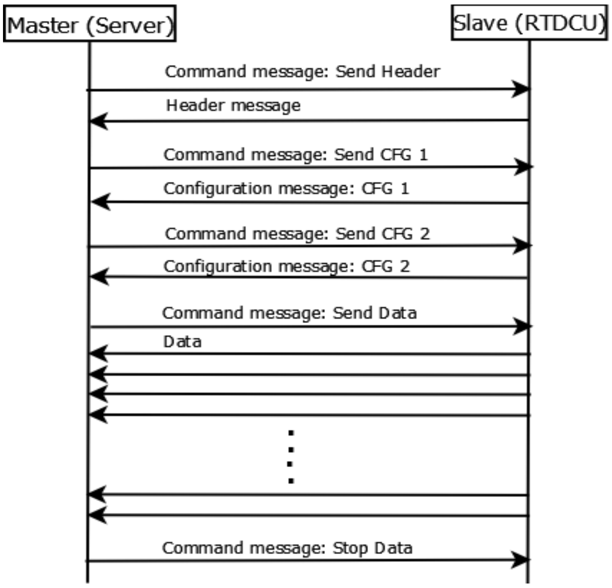

Figure 3. Data flow between RTDCU and server

The RTDCU are the measurement nodes which communicate to the server 1 via respective DC and Super Data Concentrator (SDC). Similarly, the Control Unit (CU) communicates with the server 1 via respective DC and SDC and smart meters communicate to server 2 via respective DC. The RTDCU-DC-Server network sends four types of messages, viz. *command, header, configuration* and *data* as specified in the IEEE C37.118.2 standard for data communication. Figure 3 shows the message sequence chart for the exchange of these messages between RTDCU (slave) and server (master). The command message flows from server to RTDCU and all remaining three messages flow from RTDCU to server as per the directions set based on the command messages.

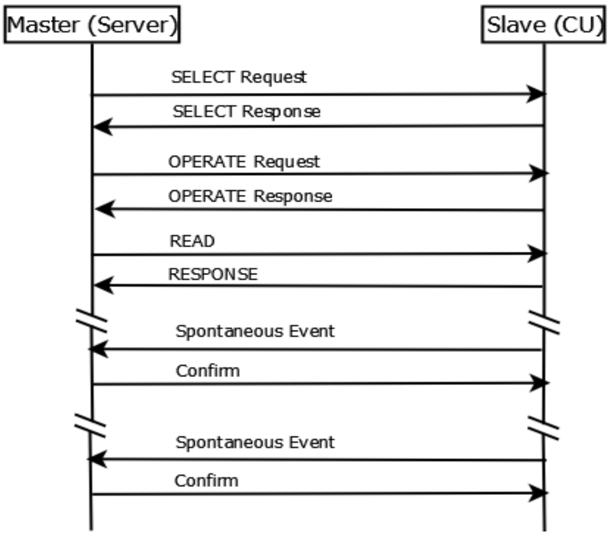

Figure 4. Data flow between CU and server

The CU-DC-Server network uses six message types, viz. *select, operate, read, response, confirm* and *spontaneous event* for achieving control action as specified in the IEEE 1815-2012 standard. Among these messages, requests for *select, operate, read* and *conform* are sent by the server to the CU, and, response for *select, operate, read*, and, *response* and *spontaneous event* notifications are sent by the CU to the server. Figure 4 shows the message sequences for the exchange of these messages between CU (slave) and server (master).

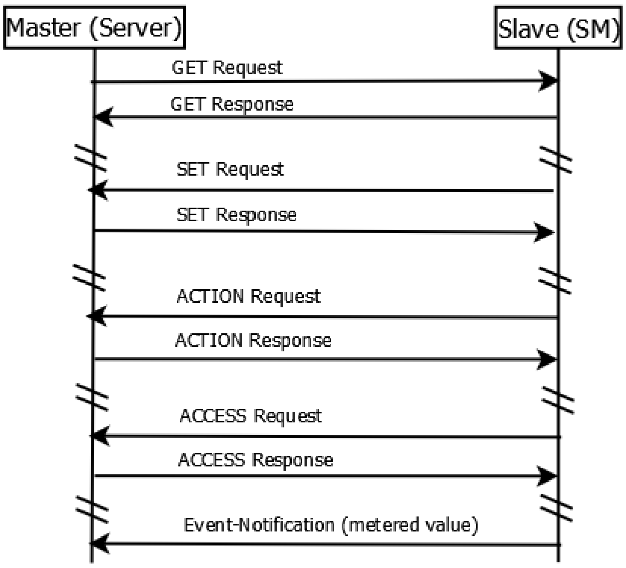

Figure 5. Data flow between SM and server

The SM-DC-Server network has four types of message, viz. *get, set, action* and *access* with each type further classified as *request* and *response* classes as specified in IEC 62056 standard. Figure 5 shows the data flow for the exchange of these messages between SM (slave) and server (master).

Since the RTDCU nodes can measure only one voltage and one current simultaneously, two such devices are required for complete data collection on bus 1. Similarly, placement of all the RTDCU, CU, DC, SDC, etc. are done on the respective buses based on the functional capabilities. The standards for respective services define the message format and sequence of communication from node to node; yet the technology for each link to establish the network communication needs to be selected. In the present work, the simulation of communication network for microgrid has been carried out in the network simulation tool, NetSim, with multiple communication technologies like IEEE 802.3 (Ethernet), 802.11 (Wi-Fi), 802.15.4 (Zigbee), etc. to help the selection of suitable technology for various links in the network and also to gauge the performance of the resultant network.

5 bus microgrid communication network with IEEE 802.3

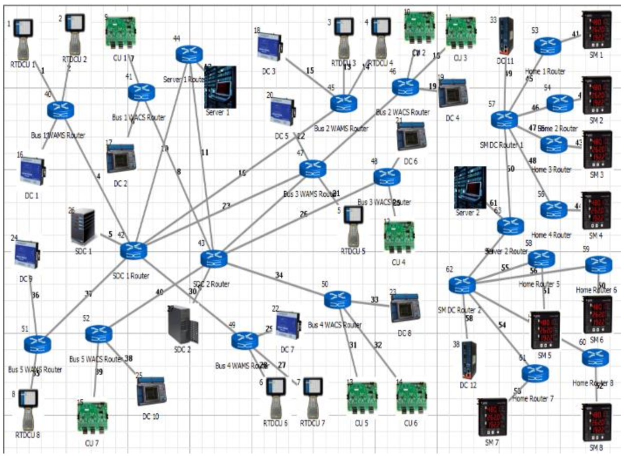

Figure 6. 5-bus microgrid communication network with IEEE 802.3 in NetSim

Figure 6 shows the communication network with IEEE 802.3 communication technology in NetSim. The RTDCU, CU, SM, DC, SDC, and servers are set up in NetSim for data exchange as per the respective standards. The RTDCU and CU are connected to DC via ethernet routers at each bus. Further, the DC to SDC and SDC to server connection are via respective routers in NetSim to accomplish WAMS and WACS. The SM in the AMI network are connected to DC via individual routers and DC to server via a common router.

5 bus microgrid communication network with IEEE 802.11

Figure 7 shows the communication network with IEEE 802.11 communication technology in NetSim. All the nodes of the system are setup and configured to achieve communication for WAMS, WACS and AMI services via IEEE 802.11 standard. The RTDCU and CU are connected to DC via access points at each bus. Each SM is made part of the network through an access point. The SDC and servers have their own access points and all these access points are linked via routers to complete the data transfer.

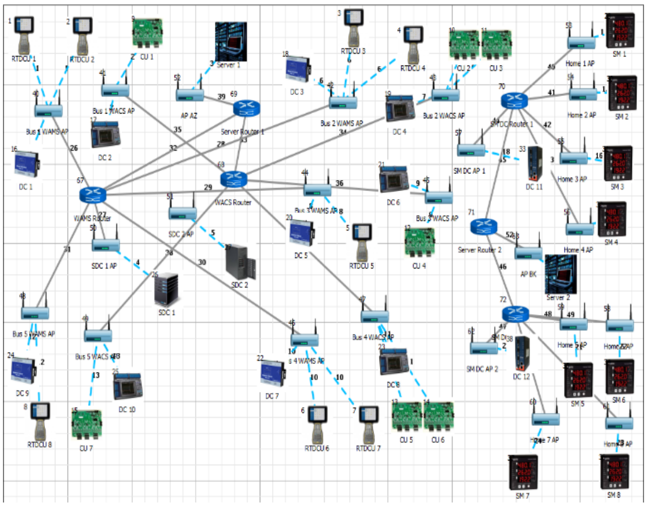

Figure 7. 5-bus microgrid communication network with IEEE 802.11 in NetSim

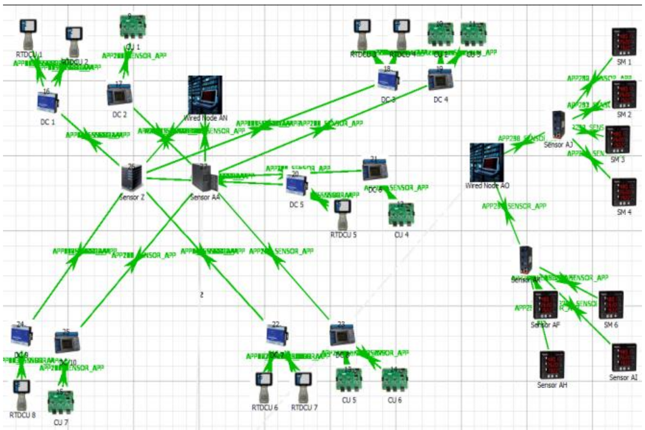

Figure 8. 5-bus microgrid communication network with IEEE 802.15.4 in NetSim

Figure 8 shows the communication network with IEEE 802.15.4 communication technology. The sensing, actuation, intermediate nodes and sink nodes are arranged and configured in NetSim for recognizing the microgrid communication network. As low range - low data rate RF technology (using free ISM band) is used, the nodes are to be placed physically close, else more intermediate nodes will be needed to reach the same distance. All the nodes directly talk to one another by unicast or multicast concepts. The data size reaching both servers being large, these are interfaced via routers to a

Low Power Wireless Personal Area Network (LoWPAN) gateway to interact with the 802.15.4 network.

Communication Network for the 5 bus Microgrid

The simulation results depict the performance indices of all the selected technologies in accomplishing the required smart services for the chosen microgrid. A comprehensive analysis of the results has been carried out below to decide the choice of technology for various links and services of the network.

Table 1. Selected performance indices with IEEE 802.3

Services		*Performance Indices*		
		PDR (%)	Delay (µs)	Throughput (Mbps)
WAMS	Command	100	98.98	52.36
	Configuration	100	944	86.69
	Data	100	202.8	67.99
	Header	100	138.25	56.39
WACS	Select	100	34.765	57.795
	Operate	100	33.385	54.775
	Read	100	35.96	57.02
	Event	100	35.15	54.905
AMI	Get/Set/Action/Access Request	100	49.4	61.87
	Get/Set/Action/Access Response	100	63.3	63.33

Table 1 presents a summary of the simulation results with IEEE 802.3. As it employs wired medium with acknowledgement based TCP scheme, the packet delivery ratio is 100 % for all the messages exchanged. This parameter represents the availability and correctness of the communication system used. Response capability of the communication network employed, captured as round trip delay, in message exchange shows that the latency varies from 35.15 to 944 µs which is well within the thresholds for monitoring, control and metering applications as per the respective standards. Application throughput which indicates the capability of a node to transmit a message varies within the range 52.36 to 86.69 Mbps, well satisfying the limits imposed by the standards of the applications considered. The protocol overhead time, that reveals the time taken for the concerned protocol to send the data from the instant it is received, ranges from 29 to 243 µs. Protocol overhead in terms of bytes of data added as header and footer for control and management ranges from 54 to 162 bytes.

Table 2. Selected performance indices with IEEE 802.11

Services		*Performance Indices*		
		PDR (%)	Delay (µs)	Throughput (Mbps)
WAMS	Command	97.02	5760.7	2.70
	Configuration	93.81	9661.4	7.64
	Data	94.02	6464.6	3.81
	Header	100	6644.9	3.01
WACS	Select	100	5710.5	2.98
	Operate	100	5554.7	2.84
	Read	98.07	5546.7	3.01
	Event	100	5427.2	2.84
AMI	Get/Set/Action/Access Request	100	6338.4	3.35
	Get/Set/Action/Access Response	100	7039	4.05

Table 2 presents the summary of the simulation results of the microgrid communication network with IEEE 802.11. As the simulation with IEEE 802.11 employs wireless medium the packet delivery ratio, even with acknowledgement based TCP scheme, ranges from 93.81 to 100 % for all messages exchanged. Round trip delay in message exchange varies from 5427.2 to 9661.4 µs and application throughput varies from 2.70 to 7.64 Mbps; both are well within the thresholds as per the respective standards of the applications considered. The protocol overhead time ranges from 70 to 9134 µs and protocol overhead in terms of data varies from 72 to 246 bytes.

Table 3 presents the summary of the simulation results with IEEE 802.15.4. As this simulation employs wireless medium and a technology that supports low data rate and range, the packet delivery ratio ranges from 83.42 to 100 % for all messages exchanged. Round trip delay in message exchange varies from 8025.6 µs to 1.3 s, and, application throughput varies within the range from 28 to 233 kbps. Both are well within the thresholds for all applications except monitoring as per the respective standards. The protocol overhead time ranges from 5120 to 320960 µs and protocol overhead in terms of data varies from 33 to 298 bytes.

Table 3. Selected performance indices with IEEE 802.15.4

Services		***Performance Indices***		
		PDR (%)	Delay (µs)	Throughput (Mbps)
WAMS	Command	83.42	737910	0.224
	Configuration	96.32	131968	0.171
	Data	96.40	1297327	0.031
	Header	95.24	8025.6	0.219
WACS	Select	91.67	690913	0.227
	Operate	96.15	430811	0.224
	Read	98.19	330389	0.224
	Event	88.14	419460	0.212
AMI	Get/Set/Action/Access Request	95	893590	0.233
	Get/Set/Action/Access Response	100	188873	0.226

IEEE 802.3 clearly outscores the other two and 802.11 has better results than 802.15.4. A comparison of all these simulation results clearly establishes the feasibility of using IEEE 802.3 and 802.11 networks for all applications in distribution domain. Also it is evident that 802.15.4 satisfies operational requirements for all applications except real time wide area situational awareness. The link-wise analysis of performance indices shows that the data flow from measuring node to data collector in all message types of all applications (WAMS, WACS and SM network), except for the data transfer in WAMS messages, can be realized using 802.15.4. Even though wired LAN outperforms the other two technologies considered, a closer look at these results shows that wired LAN and wireless LAN remain underutilized in the microgrid communication perspective. The use of WPAN will abate the issue of underutilization found in wired LAN or wireless LAN. Yet, the backhaul link from DC and all the way up to the server via SDC must have 802.3 or 802.11 in order to have acceptable *throughput* and *round trip delay* for the applications.

In addition to the performance parameters obtained via communication network simulation, a cost-benefit analysis of communication technologies is also essential for the selection of the best fit technologies. Considering scalability, in terms of addition and deletion of member nodes of the network, WPAN and wireless LAN outperform wired LAN. Wired LAN has a big disadvantage that the need of a wired communication medium and associated infrastructural systems for data transfer introduces a large cost factor. Wireless LAN, like WPAN, does not need a medium but has more infrastructural requirements than WPAN. Power-aware operation, support to redundancy and dynamic reconfiguration of the network with minimal infrastructural systems are some factors that let WPAN score over wireless LAN and wired LAN.

Considering the utilization, requirements and the cost-benefit analysis and as evident from the simulation results, the best choice is a heterogeneous network with 802.15.4 (WPAN protocols) to interconnect measuring and control nodes with the DCs and 802.3 (Wired LAN protocols) or 802.11 (Wireless LAN protocols) to link DCs and server via SDCs.

Conclusion and Future Work

This paper presented a study in which communication network for a microgrid has been simulated, using three communication technologies, viz. 802.3, 802.11 and 802.15.4, and the network communication performance indices have been studied. The simulation included message passing for various applications which are classified as monitoring, control and metering in a smart distribution grid and governed by the IEEE C37.118.2, IEEE 1815-2012 and IEC 62056 standards respectively. The analysis of simulation results shows that 802.3 and 802.11 satisfy communication requirements of all applications but remains underutilized, whereas 802.15.4 satisfies requirements all applications except monitoring messages. The study infers that a heterogeneous network combing 802.15.4 (low rate with either 802.3 or 802.11 is the best choice for realizing the communication demands of the microgrid.

The proposed network treats all applications with specific hierarchical communication structure which limits interoperability of applications. Interoperable communication architectures can be explored next to improve interoperability and coexistence of applications.

References

[1] H. Gharavi and R. Ghafurian, "Smart Grid: The Electric Energy System of the Future [Scanning the Issue]," Proceedings of the IEEE, vol. 99, no. 6, pp. 917-921, 2011. https://doi.org/10.1109/JPROC.2011.2124210

[2] E. Ancillotti, R. Bruno and M. Conti, "The role of communication systems in smart grids: Architectures, technical solutions and research challenges," Computer Communications, vol. 36, no. 17-18, pp. 1665-1697, 2013. https://doi.org/10.1016/j.comcom.2013.09.004

[3] R. H. Lasseter and P. Paigi, "Microgrid: a conceptual solution," IEEE 35th Annual Power Electronics Specialists Conference, Aachen, Germany, June 20-25, 2004, pp. 4285-4290. https://doi.org/10.1109/PESC.2004.1354758

[4] A. Bani-Ahmed, L. Weber, A. Nasiri and H. Hosseini, "Microgrid communications: State of the art and future trends," International Conference on Renewable Energy Research and Application, Milwaukee, WI, October 19-22, 2014, pp. 780-785. https://doi.org/10.1109/ICRERA.2014.7016491

[5] S. Nithin, K. K. Sasi and T. N. P. Nambiar, "Development of Smart Grid Simulator," Proceedings of National Conference on Power Distribution, Bangalore, India, 2012.

[6] M. H. Cintuglu, O. A. Mohammed, K. Akkaya and A. S. Uluagac, "A Survey on Smart Grid Cyber-Physical System Testbeds," IEEE Communications Surveys & Tutorials, vol. 19, no. 1, pp. 446-464, 2017. https://doi.org/10.1109/COMST.2016.2627399

[7] R. Podmore and M. R. Robinson, "The Role of Simulators for Smart Grid Development," IEEE Transactions on Smart Grid, vol. 1, no. 2, pp. 205-212, 2010. https://doi.org/10.1109/TSG.2010.2055905

[8] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati and G. P. Hancke, "A Survey on Smart Grid Potential Applications and Communication Requirements," IEEE Transactions on Industrial Informatics, vol. 9, no. 1, pp. 28-42, 2013. https://doi.org/10.1109/TII.2012.2218253

[9] Michael Emmanuel and Ramesh Rayudu, "Communication technologies for smart grid applications: A survey," Journal of Network and Computer Applications, Volume 74, pp. 133-148, 2016. https://doi.org/10.1016/j.jnca.2016.08.012

[10] V. K. Sood, D. Fischer, J. M. Eklund and T. Brown, "Developing a communication infrastructure for the Smart Grid," IEEE Electrical Power & Energy Conference (EPEC), Montreal, QC, 2009, pp. 1-7. https://doi.org/10.1109/EPEC.2009.5420809

[11] IEEE Standard for Synchrophasor Data Transfer for Power Systems, IEEE Standard C37.118.2, 2011. https://doi.org/10.1109/IEEESTD.2011.6111222

[12] IEEE Standard for Electric Power Systems Communications-Distributed Network Protocol (DNP3), IEEE Standard 1815, 2012. https://doi.org/10.1109/IEEESTD.2012.6327578

[13] Electricity metering - Data exchange for meter reading, tariff and load control - Part 21: Direct local data exchange, IEC Standard 62056-21, 2002.

[14] David E. Bakken, Richard E. Schantz, Richard D. Tucker, "Smart Grid Communications: QoS Stovepipes or QoS Interoperability?," Washington State University, Pullman, WA, Technical Report TR-GS-013, 2009.

[15] R. Ma, H. Chen, Y. Huang and W. Meng, "Smart Grid Communication: Its Challenges and Opportunities," IEEE Transactions on Smart Grid, vol. 4, no. 1, pp. 36-46, 2013. https://doi.org/10.1109/TSG.2012.2225851

[16] M. Caserza Magro, M. Giannettoni, P. Pinceti, M. Vanti, "Real time simulator for microgrids," Electric Power Systems Research, Volume 160, pp. 381-396, 2018. https://doi.org/10.1016/j.epsr.2018.03.018

[17] Shiva Poudel, Zhen Ni, Naresh Malla, "Real-time cyber physical system testbed for power system security and control," International Journal of Electrical Power & Energy Systems, Volume 90, pp. 124-133, 2017. https://doi.org/10.1016/j.ijepes.2017.01.016

[18] Ji-Heon Lee, Hyun-Jun Kim and Byung-Moon Han, "Hardware simulator for dynamic performance analysis of DC microgrid system," IEEE Vehicle Power and Propulsion Conference, Seoul, 2012, pp. 1491-1497. https://doi.org/10.1109/VPPC.2012.6422586

[19] Ram Mohan Reddi and A. K. Srivastava, "Real time test bed development for power system operation, control and cyber security," North American Power Symposium, Arlington, TX, 2010, pp. 1-6. https://doi.org/10.1109/NAPS.2010.5618985

[20] S. Téllez et al., "National Laboratory of Smart Grids (LAB+i) at the National University of Colombia-Bogotá Campus," IEEE PES Transmission & Distribution

Conference and Exposition - Latin America (PES T&D-LA), Medellin, 2014, pp. 1-6. https://doi.org/10.1109/TDC-LA.2014.6955185

[21] Vellaithurai C.B., Biswas S.S., Liu R., Srivastava A., "Real Time Modeling and Simulation of Cyber-Power System," Khaitan S., McCalley J., Liu C. (eds) Cyber Physical Systems Approach to Smart Electric Power Grid, Power Systems. Springer, Berlin, Heidelberg, 2015, pp 43-74. https://doi.org/10.1007/978-3-662-45928-7_3

[22] Eklas Hossain, Ersan Kabalci, Ramazan Bayindir, Ronald Perez, "Microgrid testbeds around the world: State of art," Energy Conversion and Management, Volume 86, pp. 132-153, 2014. https://doi.org/10.1016/j.enconman.2014.05.012

[23] Nithin S., Sivraj P., Sasi K. K. and R. Lagerstöm, "Development of a Real Time Data Collection Unit for distribution network in a smart grid environment," Power and Energy Systems: Towards Sustainable Energy, Bangalore, 2014, pp. 1-5. https://doi.org/10.1109/PESTSE.2014.6805323

[24] Prakash V.C., Sivraj P., Sasi K.K., "Communication Network of Wide Area Measurement System for Real-Time Data Collection on Smart Micro Grid," Dash S., Bhaskar M., Panigrahi B., Das S. (eds) Artificial Intelligence and Evolutionary Computations in Engineering Systems, Advances in Intelligent Systems and Computing, vol 394. Springer, New Delhi, 2016, pp 163-172. https://doi.org/10.1007/978-81-322-2656-7_15

[25] Neeraja T.P., Sivraj P., Sasi K.K., "Wide Area Control Systems (WACS) Implementation Based on Sensor Network Concepts," Procedia Technology, Volume 21, pp. 303-309,2015. https://doi.org/10.1016/j.protcy.2015.10.035

[26] Smitha, P.K., Sivraj, P., Sasi, K.K., "Zigbee based communication network for smart meter message passing", International Journal of Applied Engineering Research, Vol. 10, Issue: 20, pp. 18480-18484, 2015.

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