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Future strategic plan analysis for integrating distributed renewable generation to smart grid through wireless sensor network: Malaysia prospect

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A B S T R A C T

Integration of Distributed Renewable Generation (DRG) to the future Smart Grid (SG) is one of the important considerations that is highly prioritized in the SG development roadmap by most of the countries including Malaysia. The plausible way of this integration is the enhancement of information and bidirectional communication infrastructure for energy monitoring and controlling facilities. However, urgency of data delivery through maintaining critical time condition is not crucial in these facilities. In this paper, we have surveyed state-of-the-art protocols for different Wireless Sensor Networks (WSNs) with the aim of realizing communication infrastructure for DRG in Malaysia. Based on the analytical results from surveys, data communication for DRG should be efficient, flexible, reliable, cost effective, and secured. To meet this achievement, IEEE802.15.4 supported ZigBee PRO protocol together with sensors and embedded system is shown as Wireless Sensor (WS) for DRG bidirectional network with prospect of attaining data monitoring facilities. The prospect towards utilizing ZigBee PRO protocol can be a cost effective option for full integration of intelligent DRG and small scale Building-Integrated Photovoltaic (BIPV)/Feed-in-Tariff (FiT) under SG roadmap (Phase4: 2016–2017) conducted by Malaysia national utility company, Tenaga Nasional Berhad (TNB). Moreover, we have provided a direction to utilize the effectiveness of ZigBee-WS network with the existing optical communication backbone for data importing from the end DRG site to the TNB control center. A comparative study is carried out among developing countries on recent trends of SG progress which reveals that some common projects like smart metering and DRG integration are on priority.

Contents

Abbreviations: AES, advanced encryption standard; AMI, advanced metering infrastructure; AMR, automatic meter reading; APL, application layer; BIPV, building-integrated photovoltaic; DRG, distributed renewable generation; FiT, feed-in-tariff; GPRS, general packet radio service; GPS, global positioning system; ICT, information and communication technology; LOS, line of sight; NWL, network layer; PAN, personal area network; PHEV, plug-in-hybrid electrical vehicle; PLC, power line communication; RE, renewable energy; SCADA, supervisory control and data acquisition; SG, smart grid; TNB, Tenaga Nasional Berhad; WEP, wired equivalent security; WiMAX, worldwide interoperability for microwave access; WLAN, wireless local area network; WS, wireless sensor; WSN, wireless sensor network

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1. Introduction

Environmental impact is a challenge due to carbon emissions and greenhouse effect from fossil fuels that has grown over the past ten years about 4–5 times greater than for the preceding 10 years. The consequences of global warming disturb natural ecosystem such as melting polar ice caps and mountain glaciers, rising sea level, and coastal inundation that would alter forests, crop yields, water supplies, and could lead to famine [1,2]. Taking these environmental issues as concern, the Prime Minister of Malaysia announced at United Nation Climate Summit (September 2014) to pursue the establishment of targeting 40% reduction in CO_2 emissions that was made in the 2009 Copenhagen Climate Change Convention through new policies towards a cleaner and sustainable future. This has also added a dimension to the tenth Malaysia plan (2011–2015) to reduce CO_2 emission per capita from 6.7 tones (data on 2007) to a minimum level. To establish this plan, the government has taken an initiative to produce 985 MW Renewable Energy (RE) by installing large scale Distributed Renewable Generation (DRG) as well as Feed-in-Tariff (FiT) in 2015. Malaysia national utility company, Tenaga Nasional Berhad (TNB) is continuing research on Smart Grid (SG) or intelligent grid system where large scale DRG (for instance, TNB initiated 50 MW solar power plant in province of Kedah) and FiT (1–5 MW for 21 years applicable to specific RE sources set by Sustainable Energy Development Authority of Malaysia) will be integrated. With this, TNB has pointed out that the challenge of finding solution for electricity generation from RE power plants has to be effectively and efficiently integrated into the national grid for providing reliable and uninterrupted electricity to the consumers [3–5].

SG is the future intelligent and fully automated energy management system where a bidirectional communication is the fundamental requirement for integrating Advanced Metering Infrastructure (AMI), distributed generation, power generation monitoring and regulation, and demand management [4,6–8]. However, like many other countries, Malaysia's existing power grid is not yet improved with current generation information and communication technologies; so a unidirectional energy flow from generation to the consumer persists. Due to the lack of bidirectional communication technologies in SG, TNB is not having real-time information about actual DRG or FiT production that fluctuates with climate change. In this situation, TNB cannot balance between the consumer load and the supply of electricity through demand management and energy forecasting program. Also, TNB control center is neither able to detect any fraudulent act or tampering with FiT meter nor disconnect it remotely. With this, TNB cannot motivate its consumers to reduce the consumption at peak-hour by updating their real-time FiT production in energy portal/mobile apps (some studies show 5–15% energy reduction is possible [8] by applying this method). However, there are some challenges in implementing the DRG/FiT data communication in Malaysian perspective. To start with, DRGs are currently situated at different remote locations where wired communication infrastructure may not be feasible or cost effective. For instance, 10.25 MW solar power plant in Negeri Sembilan is already commissioned at the southern part and another 50 MW will be implemented at Kedah, northern part of peninsular Malaysia. In addition, FiT and other small DRGs are scattered all over the peninsular and Borneo Malaysia. To integrate these remote locations to the TNB control center, wireless technology at the distribution area could be more viable and inexpensive than wired communication.

To develop both FiT and DRG communication networks, wireless communication technology can be considered because its ease of installation and lower operating cost. However, it has limitation on interference and spectrum resource [9]. In spite of these constraints, wireless technology is recommended as it is more feasible and advantageous over wired-line technology, based on the network structure analysis of SG by many researchers [10–13]. ZigBee or ZigBee PRO is one of the wireless technologies recognized by IEEE802.15.4 standard. It is facilitated by low power energy consumption, inexpensive, better coverage, simpler wireless connectivity, and relaxed throughput. Moreover, it supports one of the unlicensed frequency bands 2.4 GHz suitable in Malaysia. ZigBee PRO is the latest released device (October 2007) that has additional facility over ZigBee such as bigger memory size, higher number of nodes integration, multicasting capability, and higher security [14].

In general, ZigBee offers better capabilities over Wi-Fi with respect to energy consumption in sensor based mesh network. Even though ZigBee has low data rate and vulnerability to interference when co-existing with Wi-Fi, it is proposed by many researchers in various applications of SG where urgent and critical data demand is not crucial [14–20]. Based on these researchers, the communication backbone of the SG which links the DRG and the control center should be wired-line. Batista et al. [15] have tested ZigBee implementation in solar, wind, and also home energy management system where in general no significant interference with other transmission and power signal is detected. However, there are some researches that have addressed the interference problem between ZigBee and Wi-Fi and have it resolved [21–23]. A delay sensitive data of wind turbine are monitored through ZigBee-Wireless Sensor (WS) for ensuring that DRG detects the inaccuracies of the system [20]. The performance of 15 ZigBee WSN nodes is analyzed under different spectrum environments and concluded based on statistical analysis that ZigBee-WS can only be utilized in lower requirement of data rate and power application of SG [14]. Byun et al. have proposed a smart energy distribution and management system where ZigBee is particularly used for controlling and remote switching of the consumer side load [24]. ZigBee in addition to Wi-Fi, 3G and Power Line Communication (PLC) are used for maintaining communication between appliances. ZigBee based home automation system or smart home monitoring has already been implemented few years before and found flexible, effective, feasible, and secured [16]. ZigBee-BACnet coalesce for demand response can meet the real-time data import service requirement in building automation [17]. ZigBee based embedded technology has achieved efficient monitoring and transmission system where different parameters in industrial application are measured namely; vibration, temperature, electricity, and gas sensing [18]. Similar demand response under home energy management system is implemented and evaluated practically in Spain where one of the communication modes is ZigBee. That research shows slower time response when number of ZigBee nodes become hundreds; however, it is solved by applying hierarchical approach [19]. We are motivated by this trend of using ZigBee technology to consider it and further the study for integrating DRG and FiT in Malaysia grid prospect which has not been considered yet in TNB SG plan.

In this paper, different wireless communication technologies are surveyed and comparison is made among them to identify the communication standard for DRG. In this scenario, influential features, protocols, and standards of ZigBee PRO are reviewed to verify whether it can meet the communication requirement relevant for energy monitoring from DRG. Finally, this paper suggests mainly ZigBee PRO communication at DRG end network in the TNB SG roadmap. Based on data demand and variation of DRG location, it can also be recommended from general assessment that Bluetooth, Wi-Fi, 3G/General Packet Radio Service (GPRS), and wired-line technologies can be coalesced with ZigBee PRO communication.

The organization of this paper is as the follows; Section 2 explains SG communication infrastructure mainly on wireless technology and the comparison among them. Then the state-of-the-art and protocol of ZigBee PRO is described in Section 3. Sensor integrated ZigBee PRO communication strategy and its statistical model analysis is also depicted in this section. Section 4 presents the TNB initiatives, SG plan, and our contribution to this plan for implementing SG. Also comparative studies among developing countries' SG development are presented in this section. Finally, Section 5 highlights the findings of this research.

2. Communication infrastructure for SG

Data transfer wirelessly is crucial for SG system as it is involved in modernizing electricity delivery system for monitoring, protection, automatic operation for interrelated components – from the center and DRG through the distributed systems [10]. To improve monitoring and reliable services, several wireless network technologies (as example described in Fig.1) are recommended in the roadmap of the SG interoperability standards [7,25]. These wireless communication technologies are considered in renewable generation into integrate with the grid due to the latest available data rates, distance coverage, bandwidth, low cost installation, and other features. These different wireless communication technologies are described in terms of monitoring and controlling of the energy from DRG to the grid control center in the following subsections. However, ZigBee communication technology is explained explicitly since this technology is mainly proposed to deploy in communication for integrating DRG in Malaysia's future SG plan.

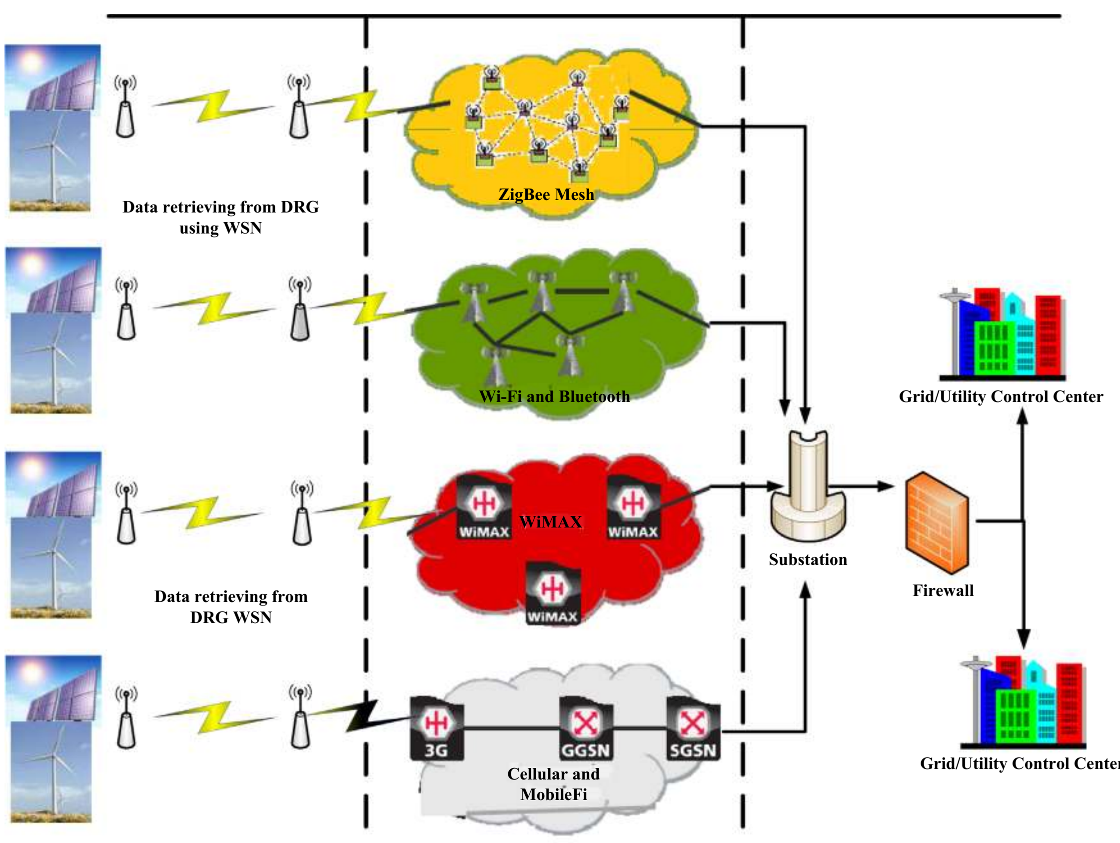

Fig. 1. Integration of DRG to the grid through different wireless communication technologies. In this network, IEEE 802.11 based Wireless Local Area Network (WLAN/Wi-Fi), IEEE 802.16 based Worldwide Interoperability for Microwave Access (WiMAX), 3rd and 4th generation (3G/4G) cellular network, IEEE 802.20 offered MobileFi, and ZigBee nominated base on IEEE 802.15 is used.

2.1. Wireless Local Area Network (WLAN)

IEEE 802.11 standard Wireless Local Area Network (WLAN)/ Wi-Fi supports point-to-point and point-to-multipoint with high speed communication technology. It also provides robustness; therefore, a number of users can share the same frequency band [26,27]. However, the interference is one of the performance limiting factors in wireless communication since some concurrent indispensable wireless transmission technologies such as wireless video surveillance systems, car alarming systems, cordless phone etc. also share same frequency spectrum along with 802.11 technology [28]. IEEE 802.11 WLAN covers four technologies: IEEE 802.11a, IEEE 802.11b, IEEE 802.11g, and IEEE 802.11n. Besides these, there is another technology called IEEE 802.11i or sometimes it is mentioned as WPA-2. Advanced Encryption Standard (AES) improves the cyber level security of WPA-2 in WLANs. All these four use the Ethernet protocol and carrier sense multiple access with collision avoidance instead of carrier sense multiple access with collision detection for path sharing [29,30]. Table 1 describes the characteristics among these four IEEE 802.11 WLAN technologies. The data rate varies for IEEE 802.11a, IEEE 802.11b, IEEE 802.11g, and IEEE 802.11n that are 54,11,20–54, and 600 Mbps respectively. Both IEEE 802.11b and IEEE 802.11g operate on 2.4 GHz, IEEE 802.11a operates on 5.8 GHz, and IEEE 802.11n operates on both 2.4 GHz and 5.8 GHz frequency bands. The distance covers for these WLAN technologies are within 100–240 m [31]; however the power of antenna makes the coverage varied. For the non-interoperable technology, 802.11b and 802.11 use only direct sequence spread spectrum. On the other hand, 802.11a and 802.11n use orthogonal frequency division multiplexing encoding scheme and multiple input multiple output technology respectively [32,33].

Implication of WLAN carries many benefits over wired LAN for monitoring DRG to the grid, as it is flexible to install, delivers mobility, and cost effective. On the other hand, Wi-Fi (IEEE 802.11b and IEEE 802.11g) uses free frequency band 2.4 GHz in most of the countries. This band allows interferences with other nearby sources and in case of occupying its limited number of all channels; the consequences will be degradation to network speed. Also, it has constraints on distance coverage in both outdoor and indoor applications [34].

2.2. WiMAX

IEEE 802.16 standard recognizes metropolitan area network for Worldwide Interoperability for Microwave Access (WiMAX) technology with certain range of frequency bands (2.3, 2.5, 3.5, and 5.8 GHz) in order to fulfill worldwide standard of interoperability for microwave access [35]. Frequency bands 3.5 and 5.8 GHz are allocated for fixed type communication and the frequency bands 2.3, 2.5 and 3.5 GHz are dedicated for mobile network communication. The data rates and covered distance range can reach up to maximum 70 Mbps and 48 km respectively [36]. Generally, license frequency bands are suited for transmitting longer distance data.

WiMAX communication is suited for wireless meter data transmission from distributed locations because of its suitability of long distance coverage with high data rate [37]. Hence, this technology becomes popular to control RE generation as well as distribution management (e.g. dynamic pricing, demand management etc.). Limited applications might suffer this technology with spectrum shortage practically in crowded and densely located area. Also, WiMAX is expensive in term of installation cost and the licensed frequency band [38].

2.3. Cellular

Green wireless sensor network, 3G and 4G cellular phone technology use 824–894 MHz and 1900 MHz license spectrums with transmission rate 60–240 kbps, respectively. Low power consumable and fully maintained (by carrier) these cellular networks offer extensive data coverage and no additional maintains cost (by user) in country wide urban and rural area. The cellular networks can be utilized in SG system without any additional network installation cost. As integration of DRG to SG is expected to increase in future, large number of consumers will be connected with DRG through transmission, distribution, and cellular service provider. The dynamics of the DRG integrated SG is the smart and efficient designing of the cellular network considering network congestion, dynamic and real-time pricing, and overall concern of reducing greenhouse gas emission [12]. In contrast, monitoring and metering of remotely installed DRG is one of the extensive applications of this technology using GPRS [10,39].

2.4. MobileFi

Another green wireless access, mobile broadband wireless access supported by IEEE802.20 standard (alternatively MobileFi) is established to ensure the reliability, low latency, frequent and high mobility, and overall high bandwidth. It uses the positive features of both IEEE 802.11 and IEEE 802.16 with licensed spectrum below 3.5 GHz. It delivers variable real-time data rates – from as low as 1 Mbps to as high as 20 Mbps. This standard of MobileFi is optimized for full mobility up to vehicular speed of 250 km/h. The implementation area in the SG is substation monitoring, Supervisory Control and Data Acquisition (SCADA) system, electrical vehicle charging system through DRG [10,40,41]. The future of implementing MobileFi is booming in wireless technology as its enhanced broadband spectrum would create an opportunity of $100 billion in the following five years through escaping of redundant cost [42].

2.5. Bluetooth

Bluetooth technology (IEEE 802.15.1) can have an important role as a wireless short range (personal area network) data transmission in SG for its suitable features such as 2.4–2.4835 GHz, unlicensed industrial scientific and medical band, and 721 kbps data rate [43]. This technology becomes economically market

Table 1
Characteristic of IEEE 802.11b, IEEE 802.11a, IEEE 802.11g, and IEEE 802.11n [32,33].

Characteristics	IEEE 802.11b (also Wi-Fi)	IEEE 802.11a	IEEE 802.11g (also enhanced Wi-Fi)	IEEE 802.11n
Data rate	11 Mbps	54 Mbps	20–54 Mbps	600 Mbps
Frequency band	2.4 GHz	5.8 GHz	2.4 GHz	2.4, 5.8 GHz
Non-interoperable technologies	Direct sequence spread spectrum	Orthogonal frequency division multiplexing	Direct sequence spread spectrum	Multiple input multiple output
Range	within 100 m	within 100 m	140 m	240 m
Non-overlapping channel	3 out of 11	8 out of 12	3 out of 11	Not found

dominating for short range network development among wireless systems which can play important role of Plug-in-Hybrid Electrical Vehicle (PHEV), fully electric vehicle or sustainable green vehicle battery charging station development in SG [44–46]. To push the green vehicle roll-out in Malaysia, 120 million RM (US $36.36 million) was funded by Malaysia government in 2013 for research and development of local automotive company, Proton electrical vehicle that will be launched by 2014 [47,48]. Fuel economy and environmental friendly these vehicles will make demand for ample number of battery charging stations each year in Malaysia (corresponding to World) which will be necessary to install in SG. The trade-off the solution is to minimize battery charging time with high power facility in each charging station. Since PHEV battery expenditure is one third of vehicle cost, its optimal performance is achieved by an efficient charging and management supervisory system as rapid growth of this green vehicle will move forward to integrate renewable sources to SG [49]. A smart communication system can assist to overcome this additional load demand. Communication for this type of PHEV charging system requires 100–255 bytes data size, 15–60 s latency, and more than 98% reliability [50]. But this arrangement encounters overloading problem in national grid while enormous number of vehicles connect charge stations at a time especially during peak hours. To solve this problem, Conti et al., 2011 has proposed a communication system using Bluetooth technology among battery charging station, vehicle management system and user's personal smart phone [46]. Building a Bluetooth communication system, vehicle battery status, charging progress, battery capacity, estimated required charging time, maximum deliverable power by charging station, charging speed, cost of charge, and other information can be monitored by sitting inside the vehicle or staying nearby charging location. Under their proposed communication system, each piconet consists of three connections such as driver's smart phone, vehicle's battery and charging station. Since numbers of vehicles can gather at the same time for charging, multiple piconet can share same channel that causes packet dropping. The simulation result shows that 20 coexist piconets can drive up approximately 27% of network collisions. Another research on PHEV battery characteristics and framework modeling was conducted by Li, and in order to validate their simulation modeling, real-time user's driving and energy monitoring system is implemented where Bluetooth communication is dedicated for collecting data by PHEV monitoring device [45].

2.6. *Influential features of ZigBee in SG*

ZigBee (IEEE802.15.4 standard), developed by ZigBee Alliance is widely useful to home management wireless communication (home automation, security management systems, remote controlling, remote meter reading, computer peripheral devices, and so on) using three unlicensed frequency spectrum (868 MHz, 915 MHz, and 2.4 GHz). Though the typical range is 10–100 m with speed 20–250 kbps, commercially available compact devices offer up to 7km (ZigBee PRO protocol) [51]. ZigBee is superior to other networks in some of the cases such as self-healing, low power consumption, support large child-nodes, and data encryption. Self-healing is the capability with guaranteed transmit data for different topologies such as star, tree, mesh. Data transmission mode in network, ZigBee can perceive the presence of additional or absence of nodes without any manual intervention within only 30 ms [18]. ZigBee topology features provide battery life saving facility, for instance fully functional as a sink node and operating functional as end nodes. In sensor based network, ZigBee PRO protocol supports more than 65,000 nodes that can be formed in an entire network. Also, 128-bit AES data encryption and integrity, and three levels security are supported by ZigBee. Besides these, ZigBee protocol supports merging features with other protocol such as BACnet for home automation system. In this application, ZigBee translates properties such as service, property–attribute, address with BACnet protocol in different layers and objects. This opportunity has brought ZigBee and BACnet to deploy in the application of controlling and managing of demand management system [14,17,52]. Another important feature of ZigBee that extends the battery life time for months is that it can be under 'sleep' mode when ZigBee is non-operational and the conversion time between 'sleep' and 'operation' mode takes only 15 ms [18].

IEEE802.15.4 supported ZigBee is from DigiMesh has two categories such as XBee and XBee-Pro. XBee-Pro is superior to XBee- as it supports few additional facilities such as self-healing, equilibrium capabilities in all nodes, enhanced Ad hoc routing vector protocol, ensuring packet delivery by acknowledgment and low power management by implementing five different sleep modes. Moreover, XBee-Pro possesses 8–30 times more transmission power than XBee that enables it to cover longer distance data transmission (up to 7km- Line of Sight, LOS [51]). Also XBee-Pro supports 13 channels and its sensitivity is -100 dBm, but XBee has -92dBm [14,15,53].

However, ZigBee has its limitations also such as low processing capabilities, longer transmission time (for large data), small delay requirement, small memory size and interference with other same frequency band such as Wi-Fi [18,21,54,55]. One of the constraints on ZigBee for practical implementation that most of the ZigBee channels overlap with IEEE802.11/Wi-Fi channels and the aftermath is performance degradation due to interference [21,55,56]. Also, coexistence of ZigBee and Wi-Fi persist interference problem within smart homes, commercial buildings and campuses [21]. The concept of overcoming interference (described in [21]), such that either 8 m distance between ZigBee and Wi-Fi or 8 MHz offset frequency is safe. Moreover, the amount of interference found in these research works was small and sometimes the interference did not show in performance degradation [15].

Considering these minor shortcomings, ZigBee is becoming popular in SG industries because of low power that yields longer battery life. Many researches are being carried out to deploy ZigBee integrated WSN in SG application areas such as energy monitoring, home automation, Automatic Meter Reading (AMR), and data management [39,40]. In this research of DRG integration with grid, ZigBee is recommended to deploy for data transmission from distributed side to gateway. For computing and sensing platform, microcontroller and ZigBee is optimum option. ATmega1281 microcontroller with 14.74 MHz frequency and 8 kB SRAM are proposed out of many embedded technologies (controller performance comparison is described in Table 2). The proposed microcontroller board is fast enough to overcome low processing capabilities and small delay requirements [57].

Multiple sensors (current and voltage, temperature, solar irradiance, wind speed, humidity, and Global Positioning System or GPS) are used for establishing last mile communication of DRG. External micro SD memory card is possible solution to be interfaced with microcontroller memory bus or gateway to enhance memory capacity so that sensors data acquisition and storage problem can be solved at remote side. An alternative option for large sensor data storage (long term monitoring scenario), external database (at control center) can be established through ZigBee gateway which is described in Fig. 2.

The comparison among wireless communication technologies such as WLAN, WiMAX, Cellular, ZigBee, MobileFi and Bluetooth have been depicted in Table 3 [10,52,58,59]. In case of data transmission and coverage, WiMAX has the highest rate 70 Mbps and up to 48 km. The nearest among highest is WLAN maximum 54 Mbps but coverage is more than 100 m. Compare to WLAN, ZigBee has 250 kbps data rate with from 100 m to 7 km (LOS) coverage. More than 65,000 nodes can be connected under a ZigBee network whereas WLAN is limited to less than 1000 nodes [14]. Bluetooth has 750 Kbps with 100 m distance acceptance but only 7 nodes can be in one network. The security system is built on different protocols of each wireless communication technology. Such as WLAN and ZigBee security systems are built on Wired Equivalent Security (WEP) Protocol, 128-bit AES encryption. WiMAX security is established on extensible authentication protocol. However, Bluetooth technology's security level is feeble compare to other technologies denoted as E0 stream cipher. Both Cellular and MobileFi use proprietary encryption system. Based on the protocol and individual performance, each wireless technology can be applied in different potential applications of SG. WLAN and Bluetooth have application in substation automation (IEC61850), monitoring and controlling distributed energy resources. WiMAX can be deployed in Wireless AMR and AMR based real-time pricing. ZigBee can be used in WSN, smart home system such as home area network. Cellular and MobileFi have utilization in Supervisory Control and Data Acquisition (SCADA), remote distribution generator monitoring, and broadband communication for PHEV.

Table 2
Comparisons among embedded technologies.

Board types	Microcontroller	SRAM	Clock speed
Arduino UNO	ATmega328	2 KB	16 MHz
Arduino Leonardo	ATmega32u4	2.5 KB	16 MHz
Arduino Due	AT91SAM3X8E	96 KB	84 MHz
ArduinoTre (*yet to be commercialized*)	Atmel ATmega32u4	2.5 KB along with 1-GHz Sitara AM335x processor	1 GHz
Waspmote	ATmega1281	8 KB	14.7456 MHz
Raspberry Pi	ARM1176JZF-S core CPU	512 MB	700 MHz
Teensy 3.1	MK20DX256VLH7 core Cortex-M4	64 KB	72 MHz
Adafruit	ATmega32u4 Core AVR	2.5 KB	16 MHz
TI Launchpad	MSP430	512 B	16 MHz

3. ZigBee as WSN for SG

3.1. Protocol and topology

ZigBee/IEEE 802.15.4 protocol plays major roles in WSN for integrating DRG to the SG. IEEE 802.15.4/ZigBee network protocol and topologies are described in Figs. 3 and 4 respectively. The protocol has architecture and each layer has own functions illustrated in Fig. 3. On the other hand, ZigBee physical and logical topology [60] which can be elaborated (described in Fig. 4) as star, peer-to-peer, and cluster-tree network [61]. Star topology is not very suitable for WSN applications because two main cons, one is power management and another is poor scalability. Peer-to-peer dominates star topology in WSN because of its efficient power management and fair usage of battery. A special type of peer-to-peer topology called cluster-tree topology where multiple nodes function as a Personal Area Network (PAN) coordinator and the others are considered as leaf of tree. The network is formed dividing into clusters lead by cluster head (CLH) or parent. The CLH acknowledges its children that are in range [62].

3.2. ZigBee node, gateway, and database

Node is consisted of transducers, radio transceiver and autonomous power supply and the output of node can be controlled by reduced instruction set computer controller with an optimum program. To enhance the capacity of sensor with node, necessary peripherals such as I/O buses, timers, analog-to-digital converter, and

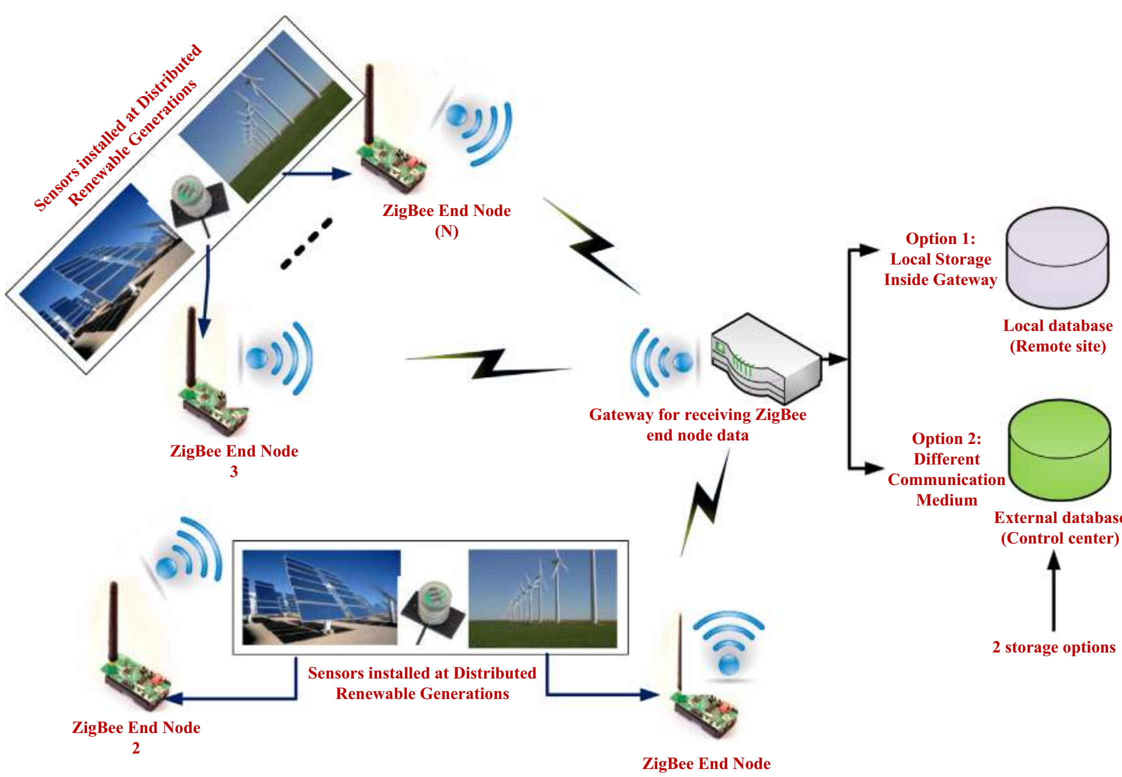

Fig. 2. Limitation of small memory problem: a solution to feeding data in local database or exporting to external database. Locally data can be stored at SD card either at ZigBee node or gateway; also large data can be exported to control center.

Table 3
Comparison among WLAN, WiMAX, Cellular, ZigBee, MobileFi and Bluetooth [10,52,58,59].

Wireless technology	Data transmission rate	Distance coverage (approximate)	Frequency	Nodes per network	Security	Potential application in SG
WLAN	From 1 Mbps to 54 Mbps	100 m to more	2.4 GHz and 5.8 GHz	> 1000	WEP, AES	1. Substation automation 2. Monitoring and controlling
WiMAX	70 Mbps	Up to 48 Km	2.3, 2.5 and 3.5 GHz	NA*	Extensible authentication protocol	1. AMR 2. Real-time pricing
ZigBee	20–250 kbps	30–100 m(7km, LOS[44])	868 MHz, 915 MHz and 2.4 GHz	65000	128-bit AES	1. WSN 2. Smart home/home area network
Cellular	240 kbps	10–50 km	824- 894 MHz/ 1900 MHz	NA	Proprietary	1. SCADA 2. Remote monitoring
MobileFi	20 Mbps	Vehicular standard	Below 3.5 GHz	NA	Proprietary	1. Broadband communication 2. Plug-in electric vehicle 3. SCADA
Bluetooth	750 kbps	1-100 m	2.4 GHz	7	E0 stream cipher	1. Online monitoring 2. Substation automation

* Not available.

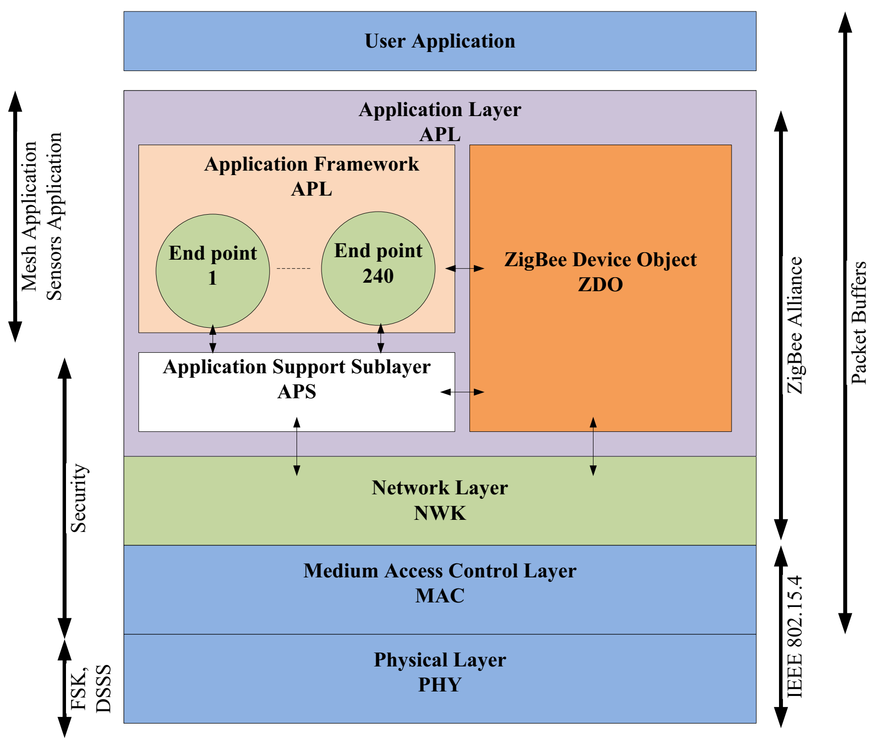

Fig. 3. IEEE 802.15.4/ZigBee layer architecture and protocol stack [63]. Network Layer (NWL) and the Application Layer (APL) are the upper layers of the IEEE 802.15.4/ZigBee protocol stack. Each layer does a specific task and communicates with each other through service access points. The NWL performs task by allocating addresses for newly joined nodes, ensuring security, and routing management over the network. On the other hand, the APL is responsible of determining devices and application service type on the network.

universal asynchronous receiver–transmitter have been prototyped (commercial name-Waspmote) in single board. Node (integrated platform of Waspmote, ZigBee PRO, and sensors) is utilized to create ZigBee PRO mesh network described in Fig. 5.

An extension of Waspmote board allows Wi-Fi communication radio to connect with an additional universal asynchronous receiver–transmitter embedded. The advantages of using ZigBee-WiFi coalesce are- Wi-Fi is Internet base protocol which can be programmed for connecting with other Wi-Fi enabled device such as router, laptop, smart phones like Wi-Fi supported devices. Also, it can be accessed for network application such as data storing file transfer protocol server. However, coexistence of Wi-Fi and ZigBee devices show insignificant performance deterioration due to channel overlapping and share similar 2.4 GHz band. This issue has been already discussed.

In this research, we have considered six key parameters for measuring from DRG site. The key important dominant parameters are voltage and current of solar or wind plants, ambient or cell temperature, humidity, solar irradiance, and wind speed [65]. Additionally GPS location is required to measure for air mass calculation [66]. Next, each node (the six sensors, ZigBee PRO communication module and microcontroller board) forwards sensor retrieved data to the destination gateway based on applied protocol.

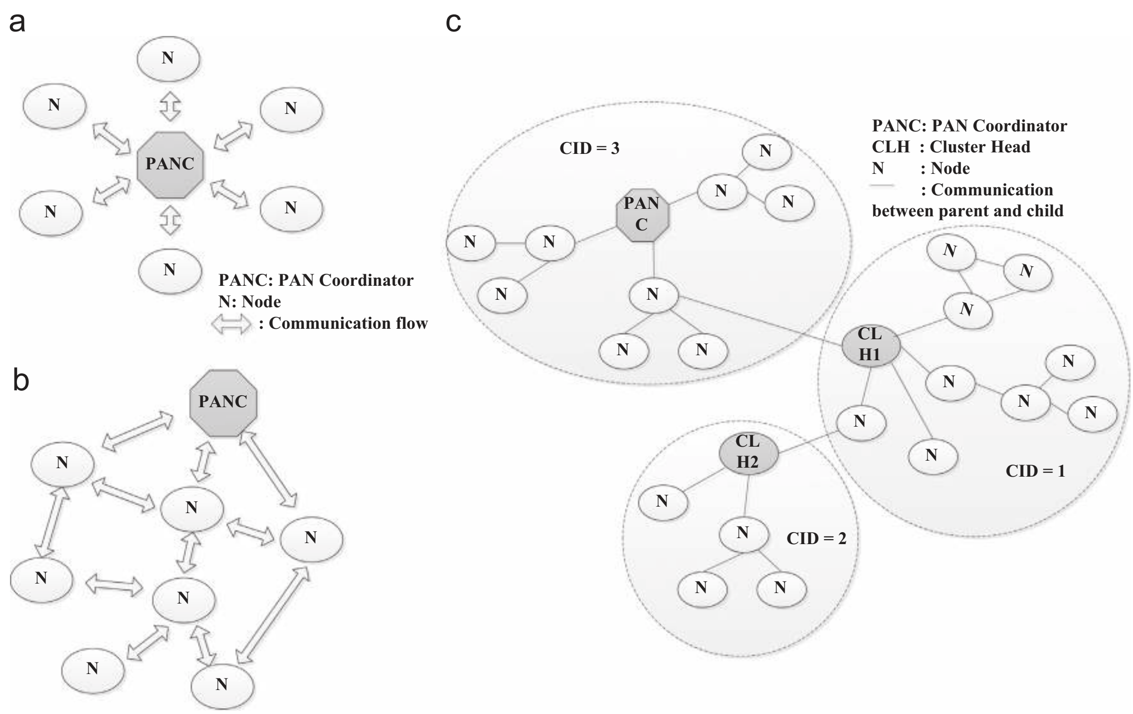

Fig. 4. ZigBee network topologies [64]. 4(a) illustrates that the coordinator represents single PAN. The communication paradigm is centralized. 4(b) describes peer-to-peer or mesh topology. Its communication paradigm is decentralized. 4(c) shows cluster-tree topology. Network is formed by dividing into cluster.

Fig. 5 depicts that one or more DRG site is connected to a gateway. To integrate the nodes, different types of gateways are proposed in [16,67–69] where the main tasks of the gateway are able to – communicate and receive data from each of sensor node placed in an allowable distance, store data into a temporary small self-database location, synchronize and forward data to an external large database located in control center, support ad-hoc Wi-Fi devices, 3G/GPRS, Ethernet, and Bluetooth connection options for exporting data to control center database or connect with a smart phone, and support data security (for instance, WEP, Pre-Shared Key (WPA-PSK) or WPA2-PSK, AES etc. authentication) from intruders.

Standard database options (local and foreign) are suitable for storing data from DRG sites. To speedup data extraction from large whole network, the smaller size local database is located in either gateway or node itself whereas the foreign large database is placed at control center. Handshaking (with acknowledgment status) protocol for synchronizing data transfer between local and foreign database is a convenient approach.

According to Fig. 5, the four gateways have created a 5 GHz or 2.4 GHz band Wi-Fi mesh communication to transfer data from either of the DRG sites to control center. The communication between DRG site1 (ZigBee-WSN) and gateway A, and site2 (ZigBee-WSN) and gateway B are established using ZigBee-gateway mesh topology. On the other hand, DRG site3 and site4 are built up on two different topologies such as ZigBee-WiFi star and ZigBee mesh respectively. In this hybrid scenario, DRG site3 and site4 are connected with gateway C through WiFi-gateway and ZigBee-gateway connection. Gateway D is 3G/GPRS enabled therefore, it can be dedicated for forwarding data to control center through Internet. The other two options for connecting to Internet are Ethernet and Wi-Fi. Either of these options can be used based on gateway location. Also gateway D is considered Bluetooth enabled communication protocol that eases any smart phone user to monitor sensors data (also be connected as Ad-hoc Wi-Fi). A cluster-tree topology is created among DRG site1, site2, gateway A, B, and D. In this special peer-to-peer topology, gateway A and B are considered the coordinator and gateway D performs as a cluster head of the network.

The gateways are operated followed by a greedy algorithm [70]. The greedy choice always finds the minimum shortage or minimum cost path for forwarding information to control center. To implement the greedy algorithm among the four gateways, we assume any graph consisted of vertices and edges where the vertex set (gateways) are $\{A, B, C, D\}$ and the edge set (gateway interconnections) are $\{AB, BC, CD, CA, BD, AD\}$.

Now, the objective is to construct a tree, T spanning from the graph such that T must be acyclic with a cost of $\psi(x, y)$ and T is the proper subset of edges (here, (x, y) is an edge). Then the total cost will be minimized when –

$\psi(T) = \sum_{(x,y) \in T} \psi(x, y)$ is minimum.

In order to build up T, the edge (x, y) is possible to determine at every iteration and append it to an edge set called P. However, the condition of appending this edge (x, y) is P must be proper subset of T (that is $P \subseteq T$) and the edge (x, y) exists such that $(x, y) \in T$, $(x, y) \notin P$. By ensuring this condition, the minimum cost of path will be determined for forwarding data among the gateways.

3.3. Modeling

From nodes integration referred in Fig. 5, the three DRG sites are modeled considering 20, 10, and 8 nodes (mesh) and the rest one has 5 nodes (star). The model is based on statistical data analysis where all the nodes are managed by mesh and star topology, sensing and acquiring data from DRG sites and forwarding to control center. In the model, a random number object is created for generating signal of each sensor node as a function of data transmission rate (T_r). At each simulation of individual DRG site, 1000 iterations are conducted under seed value $= 2$ (obtained empirically) that yields an average data transmission rate. The model depicted in Fig. 6 reveals that data transmission rate behaves as a Fourier approximation (Eq. 1) where harmonics (h) is $2 \le h \le 4$ and number of nodes (n_s) is $5 < n_s \le 20$; otherwise, data transmission rate follows polynomial characteristics (when $2 \le n_s \le 5$). From this model, Signal to Noise Ratio (SNR) and gateway sensitivity (S_G) [71] can be expressed in Eqs. 2 and 3

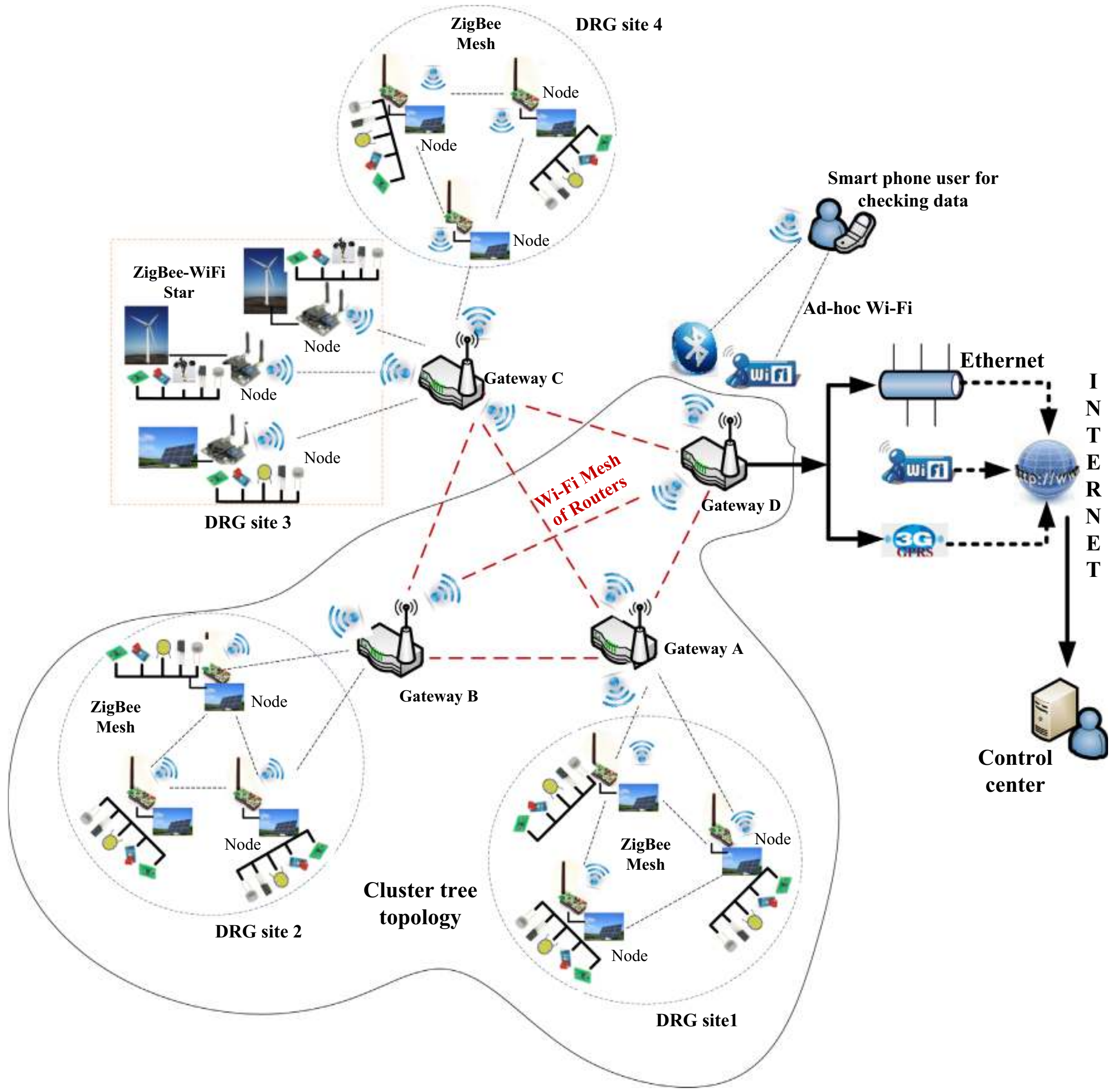

Fig. 5. Shows the integration of ZigBee PRO node, gateway, and database at DRG. At every DRG site, different type of sensors and ZigBee PRO radio are plugged into Waspmote board which is referred as node. And these nodes create a ZigBee mesh network (DRG site1, 2, and 4) or ZigBee-WiFi star network (DRG site3). Sensors (current–voltage, photoresistor, temperature, humidity, and wind) and GPS module are integrated into nodes for reading data of the renewable plants and also environment in order to measure these parameters.

respectively.

$$T_r(n_s) = \alpha_0 + \sum_{i=1}^{h} [\alpha_i \cos(h.\omega.n_s) + \beta_i \sin(h.\omega.n_s)] \quad (1)$$

$$SNR = \frac{T_r(n_s)}{B_G} \times N_D \quad (2)$$

The gateway sensitivity can be obtained by –

$$S_G = N_f + SNR + 10\log(B_z \times T_0 \times B_G) \quad (3)$$

where T_r is data transmission rate (kbps), n_s is number of nodes, h is harmonic, $\omega = \frac{2\pi}{period}$ is fundamental frequency, α_i, β_i are coefficient, SNR is signal to noise ratio (dB), N_D is noise density ratio, B_G is gateway bandwidth (GHz), N_f is noise figure (dB), B_z is Boltzman's constant (Joules/Kelvin), T_0 is absolute temperature (Kelvin), S_G is gateway sensitivity (dBm).

3.4. Security and reliability

Security and reliability of the data are ensured by performing three cryptography layers (tire1, tire2, and tire3) during hardware implementation (Fig. 7). In the first security layer (denoted as 1), all the nodes of the network are segmented to a common pre-shared key. This key is used to encrypt the information using AES-128 for ZigBee PRO. It ensures no third party devices will be able to connect to the network. In the second security layer (referred as 2), each node uses a point to point encryption scheme that prohibits the intermediate nodes of the network to see the sensor data transmitted. To perform this technique, each node interchanges with the gateway a new encryption keys using RSA-1024 (public/private encryption keys) and AES-256. The third security layer (denoted as 3) implements at the gateway end where hypertext transfer protocol secure, secure socket layer, and secure shell connections are used to send the information to the control center.

4. Smart grid projects in Malaysia

4.1. TNB initiative and SG plan

TNB has taken an initiative for end-to-end solution of its first integrated smart meter project collaborated with Universiti Tenaga Nasional, Trilliant, and Cyient. Trillian has proposed the initial plan

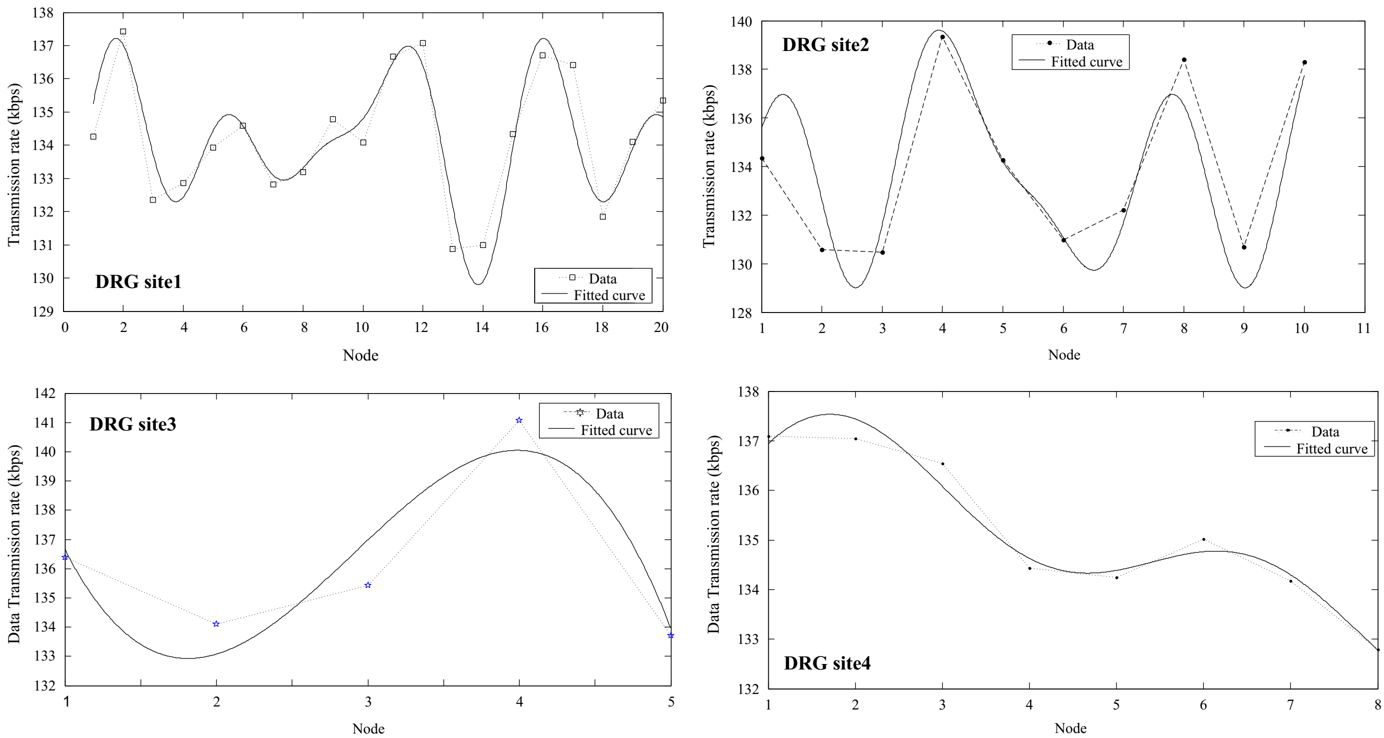

Fig. 6. Modeling of four DRG sites. DRG site1- 20 nodes are examined: $\boldsymbol{h}=4$. $\omega=0.4461$shows that the period is at 14 nodes. $\beta_3=1.47$is the highest that signifies 14-node cycle is the strongest. DRG site2- 10 nodes are examined: harmonic $\boldsymbol{h}=3$. $\omega=0.9725$shows that the period is at approximate 7 (6.5) nodes. $\beta_2=2.97$ is the highest that signifies 7-node cycle is the strongest. DRG site4–8 nodes are examined: harmonic $\boldsymbol{h}=2$. $\omega=0.5876$shows that the period is at approximate 11 (10.69) nodes. $\beta_2=1.36$ is the highest that signifies 11-node cycle is the strongest. DRG site3–5 nodes are examined: does not follow any periodic pattern; therefore polynomial is suited.

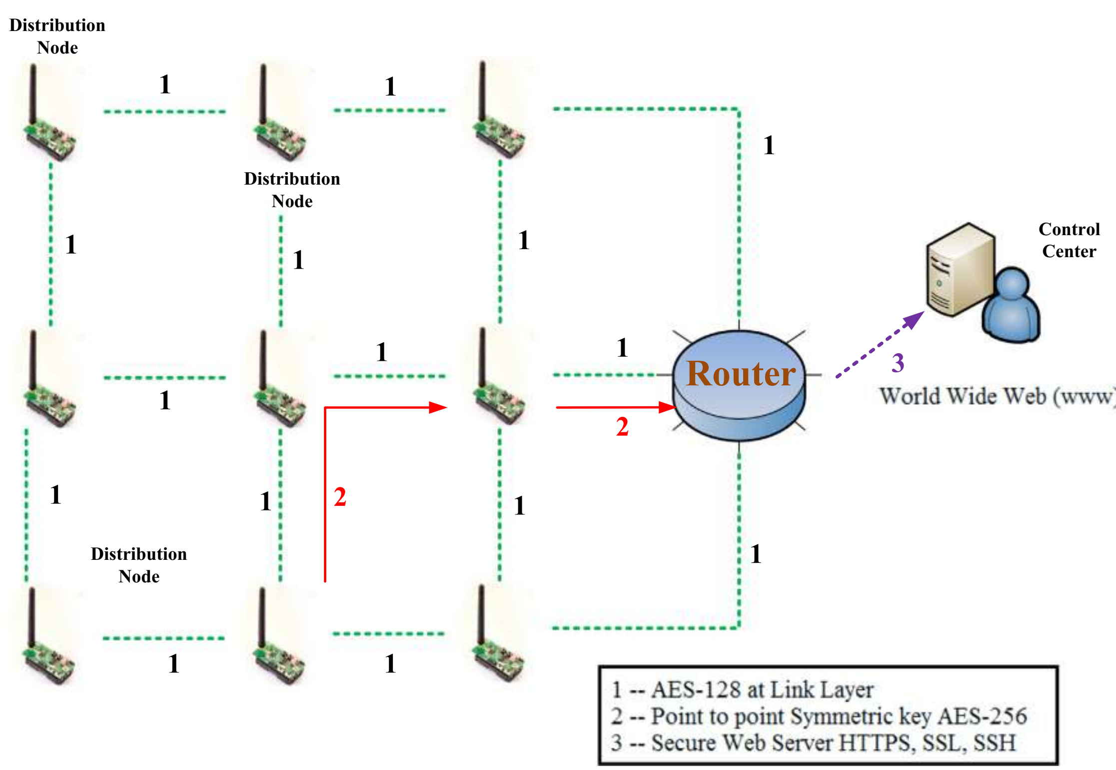

Fig. 7. Three cryptography layers for ensuring security; 1, 2, 3 denote as first, second, and third security layer respectively.

of the project communication infrastructure. As per the design plan, it will be implemented based on mesh technology dividing the communication infrastructure into two networks – neighborhood area network and wide area network. The proposed mesh technology will be operated on 2.4 GHz license-free frequency spectrum; therefore, it will not require any major regulatory changes. The project end system integration and management will be handled by one of the leading system integrators in Malaysia, Comitel [72]. Cyient has collaborated with the SG development projects by investing RM100,000 (US$ 28500.00).

TNB SG vision from 2011 to 2017, is segmented into four phases such as communication and technologies for power system automation, AMI, advanced sensing and measurement, and system integration. Each phase is comprised of several micro modules where one of the modules under phase 4 (2016–2017) is the implementation of an intelligent micro-grid with distributed RE generation. To date, TNB research has implemented some successful projects under SG visions such as WAIS-based control and protection system applications, IEC61850 for substation automation including intelligent system and monitoring, overhead transmission line real-time thermal rating, and knowledge-based analytics system for power transformer online monitoring. TNB planned SG communication and information structure is bidirectional and open standard with reliability and security. Fig. 8 shows TNB green and SG research ultimate goal which is expected to be completed by 2017 [73].

4.2. Contribution to TNB SG plan

According to TNB SG initiatives [73], data communication infrastructure of integrating RE generation to the SG grid is one of the visions which is yet to be implemented. In this respect, our research on communication for DRG supports the TNB initiative. The research plan can be implemented in two stages – system modeling and hardware implementation. In the modeling stage, any solar plant (as a DRG) scenario can be considered to have the required electrical and environmental parameters. Others features to be considered include type of sensors, sensor-packet structure, number of required embedded-communication node, ZigBee PRO antenna placement, propagation path loss, network throughput, packet loss rate and collision, and node energy consumption. The hardware implementation will be based on the system simulation. Different sensors, ZigBee PRO, and embedded board are considered as a single node for installation at the solar power plant. Since all the nodes form a mesh or star network, relevant algorithms will be developed. Then further analysis will have to be conducted on network performance to ensure effective data delivery to TNB control center. Here, a schematic diagram of about 4 km^2 urban area is assumed (Fig. 9) where distributed large scale hybrid solar-wind generation and small scale BIPV (or FiT) are integrated through ZigBee PRO communication. All the ZigBee PRO-WS nodes are installed within the LOS distance range (500 m) under the three gateways – G2, G3, and G4. Within this range, Waspmote embedded board with ZigBee PRO 5dBi antenna can communicate with each other by delivering sensor retrieve data. In this scenario, G1 gateway is a 3G/GPRS enabled as shown in Fig. 9, is considered in order to optimize the cost. Therefore, Wi-Fi and ZigBee enabled G2, G3, and G4 gateways are required to communicate and synchronize data with G1 gateway using mesh and previously presented greedy algorithm. Finally, G1 gateway can export data to the control center by 3G/GPRS or existing telecom optical network. Table 4 summarizes the complete scenario.

4.3. SG comparison studies

China has become the leader in SG not only among developing countries but it also measures-up with the developed countries like the US and Europe in recent years. As recent as 2013, 62% of households in China (40% in the US) are using smart meter and it is likely to reach nearly 100% by 2017 [74]. The country has a tremendous development in ultra-high voltage transmission system, substation automation, smart building and community, second version of IEC61850, and power distribution system automation (many of them are already put into operation). Two comprehensive successful projects namely the Shanghai Expo Demonstration Project and the Sino-Singapore Eco-City Smart Grid Demonstration Project have already been completed. However, optical fiber based communication backbone and RE integration are still on progress in China [75]. Among The Association of Southeast Asian Nations or ASEAN, Singapore has very high quality power system and is accelarating rapidly to the smarter grid through the development of many applied projects (in collaboration with

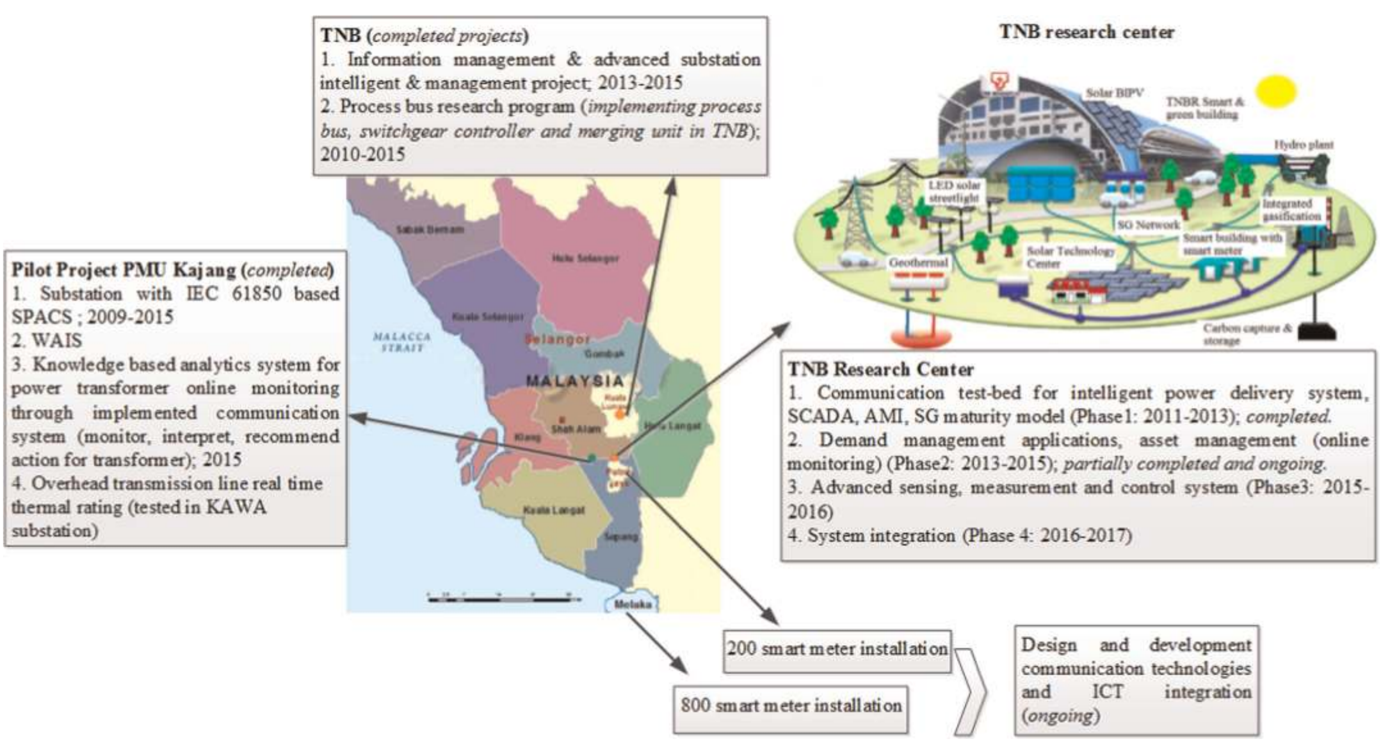

Fig. 8. TNB green and SG research; completed and ongoing projects from 2011 to 2017 [73].

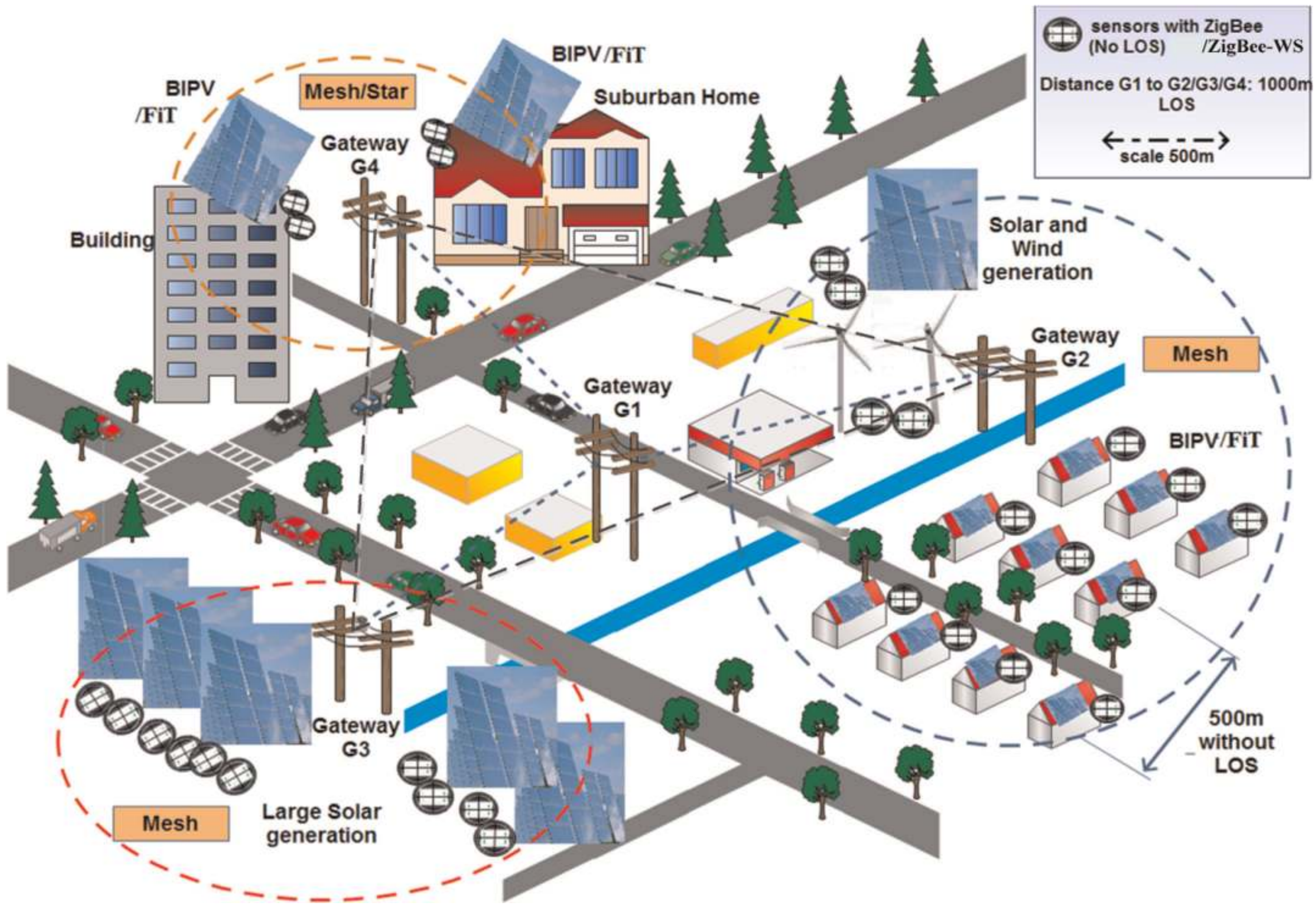

Fig. 9. Schematic diagram of an urban area – integrating gateways and ZigBee-WS node at DRG.

Table 4
Summarize of gateways and ZigBee-WS node scenario.

Node	Approx. distance between 2 nodes	Mode of communication	Topology	LOS
G1↔G2↔G3↔G4	1.5–3 km	Broadcast, Wi-Fi	Mesh	Yes
ZigBee-WSN↔ ZigBee-WSN	> 500 m	Broadcast, 2.4 GHz ZigBee	Mesh	No
ZigBee-WSN →G2/G3/G4	Within 500 m	Broadcast, 2.4GHz/ 5 GHz ZigBee	Mesh/star	No

↔ 2-way communication; → 1-way communication.

China) such as energy storage, analytics, RE monitoring and controlling, minimizing haze related threat, expert support system, and demand response in PHEV charging [76]. Among these, building management system and some of the demand response projects are already completed. In these projects ZigBee, PLC, and TV whitespace are considered [77]. Thailand's 20-year SG roadmap (2011–2030) is initiated by the Thai ministry and Provincial Electricity Authority. The highlighted sectors are AMI, increase RE generation, energy efficiency [78]. In East Asia, both India and Pakistan have common problems such as power threat, transmission and distribution losses, higher percentage of RE integration, and load management [6,79]. These issues are priority in the attainment of their SG development plan. Besides this, bidirectional communication for AMI, cognitive radio sensor networks with existing broadband system (also mesh, PLC, 3G/GPRS) are included in their plans. Malaysia SG vision has been discussed in the previous subsection. Out of four phases, phase1 (2011–2012) is already completed. It includes security assessment, loss optimization, fault location and restoration, and automatic feeder reconfiguration. Presently, TNB research is working jointly with Universiti Tenaga Nasional on phase 2 and phase 3 where wide area intelligent system or WAIS for monitoring, control, protection, and enhancement of blackouts reduction have been completed. The AMI project with 1000 smart meters installation process is ongoing in Putrajaya and Melaka. It encompasses all relevant Information and Communication Technology (ICT) infrastructure and data information system, mainly PLC and ZigBee. From the comparison scenario, it is noticeable that many developing countries have SG roadmap where the common emphasized key area is smart RE monitoring and integration to the SG through wired and/or wireless data communication technologies. Table 5 summarizes comparison of SG development plans among developing countries.

5. Conclusion

This paper has compared different wireless communication technologies and their protocols, topologies, standards, and pros and cons to find an optimized network solution for integrating DRG to the future SG in Malaysia. According to our analysis, lower data rate and relaxed throughput based wireless technology can meet the data communication requirement for monitoring and controlling of DRG. Therefore, low power and low data rate embedded ZigBee PRO technology is recommended for TNB SG plan at the distribution level

Table 5
Comparison among developing countries in SG development plans.

Key focus area	Country	Communication technology	Remarks
High voltage transmission system; demand management; RE integration	China	Optical fiber based backbone, GPS	1. Completed (2011): RE power generation, control and operation (2011); smart inspection of power lines using GPS (2012) 2. Ongoing: 3–10 GW wind farm integration and others 3. Future plan: Many [75]
AMI; demand response; RE integration, monitoring, and management; PHEV	Singapore	Many supporting vendors including ZigBee Alliance.	1. Completed: Development of last-mile communication by AMI (smart metering) infrastructure (2010–2012 and 2013) [76]; Energy Market Authority invested $10million for applied SG projects (2013–2014) [80]; Enhancement of SG design, integration and management at solar power test-bed in Pulau Ubin (2014) [80,81].
		ZigBee, PLC, and TV whitespace are considered for AMI [77].	Ongoing: demand response in electric vehicle: 2015 [82].
AMI, RE integration; energy efficiency; PHEV	Thailand	Not specified	Completed and ongoing: 100,000 smart meters install pilot project, expansion, and benefit examine (2012-2021). Future plan: RE increase and energy storage (2017-2021) [78].
AMI; system loss; RE integration	India [79], Pakistan [6].	Cognitive radio sensor networks, mesh, PLC, GPRS	Future plan: RE integration and load management; Smart metering plan
AMI; substation automation; communication for power system automation, demand management, intelligent micro-grid with RE	Malaysia	PLC, 5.8 GHz mesh, WiMAX as backbone. 2.4 GHz Mesh Network	1. Completed: wide area intelligent system or WAIS; substation with IEC 61850 with monitoring and management. 2. Ongoing: Smart metering installation with ICT infrastructure; smart street light system; demand management. 3. Future Plan: Extension of IEC 61850 at new substations, security, full integration of RE through ICT.

communication. Moreover, ZigBee PRO has other influential features over high-data rate Wi-Fi and wired-line PLC technologies such as convenient sensor integration, supports longer coverage, lower power consumption, large number of child-node integration, and better data encryption. In contrast, realizing the DRG infrastructure using ZigBee PRO technology has some shortcomings such as interference, small memory, low processing capability, longer transmission time, and others which are highlighted and resolved based on previous reviews. Notwithstanding, this study suggests the use of fiber-backbone owned by telecom Malaysia with ZigBee PRO network which can reduce additional infrastructural cost, interference, low data rate, or spectrum limitation problem. One of the most significant findings to emerge from the SG comparison study is that government bodies of developing countries, including Malaysia have huge investments and supports for moving towards SG implementation. It could be beneficial for regional development in modernizing the grids if the developing nations collaborate in terms of their experiences, efforts, and comprehensive strategy on integrating DRG.

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