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Developing the ZigBee Based Data Payload Coding for Data Communication in Microgrids

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Abstract—A data coding is presented in this paper for ZigBee-based wireless data communication system for future microgrids. It is assumed that each microgrid has a central controller and each distributed generation unit in the microgrid has a local controller. The communication system is responsible for transmitting and receiving data amongst these controllers. This communication system is based on ZigBee technology, which has low cost and low power consumption. The required data to be transferred are defined and a suitable coding is also proposed. Finally, the number of transmitted symbols and the processing time delay of the proposed data coding are numerically analyzed.

Index Terms—Communication System, Data coding, Data Transmission Delay, Microgrid, ZigBee.

I. INTRODUCTION

The increasing number of renewable energy sources such as photovoltaic, wind and micro-hydro are leading to a substantial amount of electric energy generation in the form of Distributed Generators (DGs) within the electric networks. Integration of the DGs will benefit the electric networks by reducing the network expansion costs, minimizing the power losses in long feeders and increasing the reliability of the network. They may also be helpful to achieve faster recovery following a fault in the network [1].

Microgrid (MG) is a cluster of loads, DGs and energy storages interconnected by a network of feeders and located in the same geographical area which can act as an independent power system whenever needed [2]. In the presence of a main utility grid, a microgrid can operate either in grid-connected mode or in off-grid mode. In grid-connected mode, the network voltage and frequency are dictated by the grid; hence the DGs are controlled such that the desired amount of power is supplied by each DG. In off-grid mode, the DGs are not only required to supply the MG load demand but also they should regulate the voltage and frequency within the acceptable limits. Therefore, for proper operation and control of DGs within the MG, each DG should be updated with the information about the MG operation mode. This information is required to be transferred from the MG main Circuit Breaker (CB), which interconnects the MG and the grid (as shown in Fig. 1), to all the DGs. Fig. 1 shows a sample MG network along with the different data which need to be monitored and transmitted to the respective controllers.

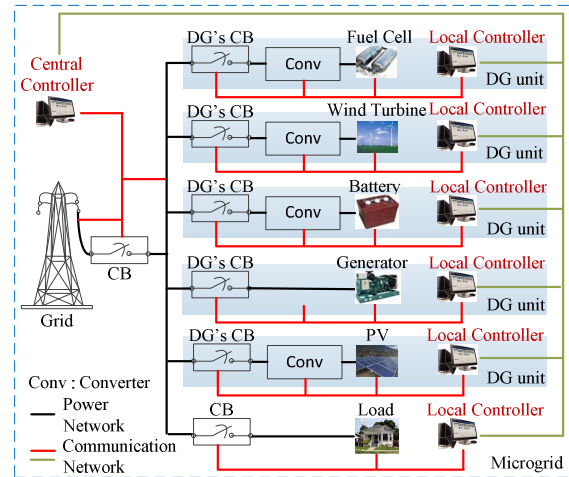


Fig. 1. Schematic of a MG system.

It is expected that in the near future all the operations in an MG will be fully automated [3]. The automation system includes fetching data from sensors, passing the data to controllers and finally passing the control commands to the actuators. Therefore, MGs need a fast and accurate data transmission system to transfer the measured data and command signals to the relevant controllers in the DG or the MG. Hence, a proper Information and Communication Technology (ICT) needs to be developed [4]. This facilitates controlling and monitoring of electricity generation and consumption as well as network remote operation.

Wired and wireless communication technologies can be employed in MGs. The popular wired technologies, used in power systems, are serial communication RS-232/422/485, bus technology (e.g. ModBus, ProfiBus, CANBus) [5], power-line communication (e.g. DLC, PLC, BPLC) [4], and Ethernet (e.g. LAN, optical cable) [5,6]. On the other hand, the popular wireless technologies, used in power systems, are cellular (e.g. GSM, CDMA) [7], Wi-Fi [7,8], WiMax [9], ZigBee [7,10,11,12], Z-Wave [13], Bluetooth [11], Insteon [14], radio frequency [11] and Microwave [14].

The wired technologies have higher data transfer bandwidth and are more reliable; however their installation cost is very high. On the other hand, the wireless technologies have less installation costs compared to the wired technologies and are more suitable for remote areas while being more flexible for future expansions [11]. A comparison among different wireless technologies that can be considered for MG applications is presented in Table I.

TABLE I
Comparisons among different wireless technologies applicable for MGs

| Technology | Range | Data Rate | Frequency | Routing | Security | Suitable for | Modulation | Installation Cost |
|----------------------|------------|------------|----------------------------------|----------------------------|---------------------------------|-----------------------|---------------------------------|-------------------|
| Cellular (GSM, CDMA) | several km | 270 kbps | 900, 1800 MHz (2G), 2.1 GHz (3G) | Direct | 64 bit A5/1, KASUMI cipher (3G) | backbone | GMSK | Costly |
| WiFi | 100 m | 54 Mbps | 2.4 GHz | more than 70 protocols | WPA | backbone | QPSK, BPSK, 16/64 QAM. | moderate |
| WiMax | several km | 30-40 Mbps | 2.3, 2.5, 3.5 GHz | AODV, DSR, OLSR and ZRP | AES and 3DES | backbone | BPSK, QPSK, 16/64QAM, OFDMA-PHY | moderate |
| ZigBee | 100-1500 m | 250 kbps | 2,4 GHz, 868, 915 MHz | AODV, HERA | AES | end devices | OQPSK, BPSK | low |
| Z-Wave | 30 m | 100 kbps | 900 MHz | source-routed mesh network | Unique ID | end devices | GFSK | low |
| Insteon | 50 m | 38 kbps | 900 MHz | Send and receive | Unique ID | end devices, backbone | BPSK | low |
| Bluetooth | 100 m | 24 Mbps | 2.4 GHz | a master-slave structure | encryption key | end devices, backbone | GFSK, DQPSK and 8DPSK | low |

By the growing number of meters, sensors and actuators which need to be monitored and controlled continuously within a MG, utilizing wired technologies leads to a significant installation cost. Therefore, the wireless technologies are a better candidate for MG applications. However, it is to be noted that they have a lower data transmission rate and can be vulnerable to interferences with other signals [8].

II. COMMUNICATION LAYERS IN MICROGRIDS

A hierarchical control system is usually required for the proper operation and control of the MG, as discussed below.

a) The local (primary) controller: This controller is the lowest control block within the hierarchical control system and is located within every DG unit [2]. This controller mainly controls the operation of a DG based on local measurements. Hence, it fetches data from the local sensors/meters using very small sampling time steps and produces the required outputs for the DG actuators.

b) The MG central controller: This is the main controller for the MG and is mainly responsible for controlling the voltage magnitude and frequency in the MG [2]. This controller receives the voltage magnitude and frequency data from the local controllers and sends back the proper reference for voltage magnitude and frequency in each DG. This controller has a larger time step in comparison to the local controllers.

c) The network tertiary controller: This controller is at the highest level in the hierarchical control system and is responsible for general control of the power network [2]. This controller can have several modules such as load forecast, electricity market, self-healing, unit-commitment, economic dispatch, etc. This controller defines if a MG should be operating in grid-connected or islanded mode, the output power of each DG unit, the interconnection of two neighboring MGs, etc.

The main data to be transferred from the local controllers of each DG to the MG central controller are the voltage (magnitude, angle, frequency) and active/reactive power and the CB status. In addition to these, the MG main CB status and the voltage magnitude within the MG (measured at one or more locations) need to be transferred to the MG central controller.

Based on the location of the communication devices as well as the characteristics of the data to be transferred, the communication technologies in the MG are classified as the following three layers, as shown schematically in Fig. 2.

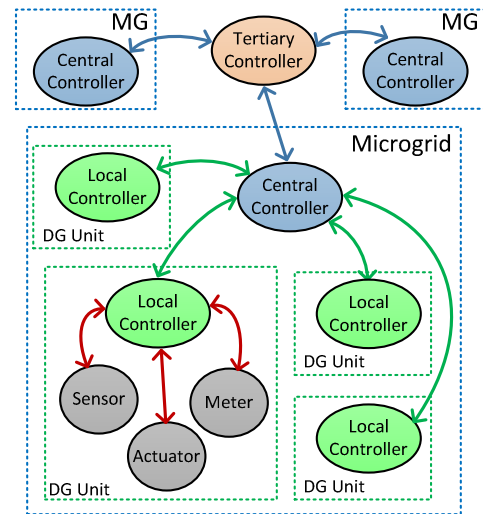


Fig. 2. Proposed hierarchical communication layer in MG.

III. ZIGBEE COMMUNICATION IN MICROGRIDS

ZigBee is an emerging wireless communication technology. It can connect directly to sensors, meters and actuators. In addition, it is a low-cost and low-power device which has less complexity for the users and is also flexible for expansion in future [11,15]. Based on IEEE Std. 802.15.4, ZigBee has data transfer rate up to 250 kbps. In addition, it is a low consumption device and hence, it can operate for a long time with only AA batteries [11]. On the other hand, ZigBee is a short range wireless communication device which can cover an area of around 300-1500 m [16].

In terms of communication capabilities, there are two types of ZigBee devices, i.e. Full Function Device (FFD) and Reduced Function Device (RFD) [17]. An RFD has the capability to connect to sensors, actuators and meters; however, it does not have the capability to communicate with other RFDs. On the other hand, an FFD has the capability to communicate with other FFDs as well as the sensors, actuators and meters [17].

Based on IEEE Std. 802.15.4, data communication in ZigBee is formulated in the following four frames [17]:

- A beacon frame, used by a coordinator, to transmit beacons. This frame is consisted of $104+(32 \text{ or } 80)+k+m+n$ bits where n is the number of beacon payload bits, m is the pending ad-

dress field bits and k is Guarantee Time Slot (GTS) field bits. Note that the (32-80) bits represent the address field.

- A Data Frame, used for transferring all the data. This frame is consisted of $88+(32-160)+N$ bits. The (32-160) bits represents addressing field bits, N is the number of data payload bits where the maximum of data payload is 888 bits.
- An Acknowledgment Frame (ACK), used for confirming successful frame reception and is consisted of 88 bits.
- The Medium Access Control (MAC) command frame which is used for handling all MAC peer entity control transfers. This frame is consisted of $96+(32-160)+u$ bits where u is the command payload bit.

The communication between the FFD/RFDs and the coordinator (in non-beacon network) starts by the coordinator requesting data from the FFD/RFDs. Then, the RFD/FFDs confirm by transmitting an ACK and the requested data. After receiving the data, the coordinator transmits the acknowledge frame to the FFD/RFDs.

Based on IEEE Std. 802.15.4, ZigBee devices are available with 868 MHz, 915 MHz and 2.45 GHz carrier frequencies. The lower carrier frequency usually has longer area coverage, e.g. the 2.45 GHz ZigBee from the Xbee-Pro from Digi International Inc. can cover an area up to 1.5 km, while the 868 and 915 MHz ZigBee from the same manufacturer can cover an area up to 40 and 14.5 km, respectively [16]. The data modulation technique for the 868 and 915 MHz ZigBee is Binary Phase-Shift Keying (BPSK) while for the 2.45 GHz ZigBee is offset Quadrature Phase-Shift Keying (OQPSK). The data transfer rate for the 868 MHz, 915 MHz and 2.45 GHz ZigBee is respectively 20, 40 Kbps and 250 Kbps [17].

In 2.45 GHz ZigBee, every 4 bits of data needs to be mapped into one symbol and each symbol is then mapped into a 32-bit-chip-PN sequence. In 868 and 915 MHz ZigBee, each data bit needs to be mapped into a symbol and each symbol is then mapped into a 15-bit-chip-PN-sequence [17]. As an example, to transmit the voltage magnitude of 220 V, measured in the MG, from RFD to FFD using 2.45 GHz ZigBee, first the 220 decimal digits need to be coded into binary digit (i.e. 1101 1100). Then, the binary digit should be mapped into symbol and each symbol to be mapped into chip-PN sequence. Fig. 3 shows schematically the data modulation processes from binary digit into a symbol and then into chip-PN sequence before spreading in the form modulated signal.

The data to be transferred should be coded such that it represents data type (i.e. voltage magnitude, voltage angle, active power, reactive power, frequency and CB status), data dimension (e.g. kilo, mega), data value (e.g. 220), RFD or FFD number, Channel number (if there is more than one sensor/actuator/meter connected to a single RFD) and DG number in MG. All these data need to be mapped into data payload section which has the maximum of 888 number of bits [17].

Data payload code can be represented in binary or text formats. As an example, voltage magnitude of 220 V in decimal digits can be represented by binary code = 1101 1100 or as text characters of 220. The binary format can be processed faster by digital devices such microcontroller and has less number of bit representation. However, the text format has more flexibility for expanding the network devices and data transactions in the MG. In addition, the binary format can be directly converted to the symbol and then into OQPSK or

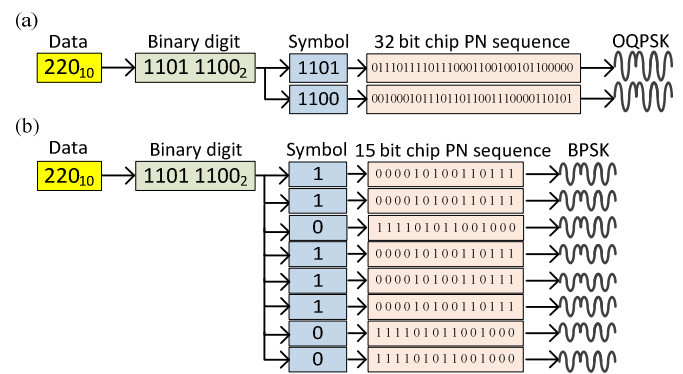


Fig. 3. An example illustrating the steps of modulating 220 V in ZigBee, (a) for 2.45 GHz ZigBee, (b) for 868 or 915MHz ZigBee.

BPSK modulator, whereas the text format first needs to be converted into binary code and then converted into a symbol. The most well-known text to binary conversion method is ASCII code [18].

Data transaction in the MG can be classified as:

1. Transferring data value where the RFD sends data to FFD or coordinator.
2. Data request transaction, where the coordinator request data value or status from the RFD (e.g. the coordinator needs data of the generated active power from a DG).
3. Command transaction, where the coordinator sends a command to the RFD (e.g. the coordinator requests RFD to open/close a CB).

To define the transaction type among the above three options, a special code needs to be developed in binary or text formats. As an example, the developed code can represent data value, data request and command transactions respectively by 01, 10 and 11 in binary format or by “VL”, “RQ” and “CM” characters in text format. Similarly, each data type can be defined in binary or text format as shown in Table II. Similarly, the commonly used dimensions of 10^0 , 10^1 , 10^2 , 10^3 , 10^4 , 10^5 and 10^6 can be represented respectively as 000, 001, 010, 011, 100, 101 and 110 in binary format or “E”, “1”, “2”, “K”, “4”, “5”, and “M” in text format.

To measure the six required data from each MG (i.e. voltage magnitude, angle and frequency, active/reactive power and CB status), maximum of 6 RFDs may be required. In addition, it is expected that no more than 4 sensors/meters /actuators are connected to the same RFD. Hence, a maximum of 3 bits are required for the RFD number and 2 bits for the channel number. The number of DGs within a MG defines the number of bits that are required to define it. As an example, assuming the number of DGs is less than 15, four bits are required to define the number of DGs in the MG. This coding in binary and text formats is given in Table III. This data payload coding is then utilized within the data payload section of the standard ZigBee Data Frame. Fig. 4(a) shows the standard Data Frame for ZigBee. The period of Data Frame in Zigbee is the sum of the period of data payload and the period of other transmitted parameters such as preamble sequence, start of frame delimiter, etc., as shown in Fig. 4(a).

Table II
 Data to be transferred in the MG, the number of bits and the binary/ text formats for each data

| Data | Data Value | | | | | Data Code | |
|---------------------|------------------|------------|---------|-----------|------------|-----------|------|
| | Range | Data steps | Step No | Bit No | Text digit | Binary | Text |
| Voltage Magnitude | 0 - 500 V | 1 | 500 | 9 | 3 | 001 | "VM" |
| | 0.00-20.00 kV | 0.04 | 500 | 9 | 5 | | |
| Voltage angle (°) | 0.0 - 360.0 | 0.1 | 3600 | 12 | 5 | 010 | "VA" |
| Frequency (Hz) | 0.0 - 60.0 | 0.1 | 600 | 10 | 4 | 011 | "FR" |
| CBs | on, off | - | 2 | 1 | 1 | 100 | "CB" |
| Active Power | 0 - 999 W | 1 | 999 | 10 | 3 | 101 | "AP" |
| | 0 - 99 kW/MW | 0.1 | 1000 | 10 | 4 | | |
| Reactive Power | 0 - 999 W | 1 | 999 | 10 | 3 | 110 | "RP" |
| | 0.0 - 99.0 kW/MW | 0.1 | 1000 | 10 | 4 | | |
| Fixed Length | | | | 12 | 5 | | |

 Table III
 Binary and text format coding for defining the number of data source, RFD/FFD and channel

| Data | Data Code | | Device | Data Code | | Channel | Data Code | |
|-------|-----------|--------|-----------|-----------|--------|---------|-----------|-------|
| | Binary | Text | | Binary | Text | | Binary | Text |
| Grid | 0000 | "Grid" | RFD/FFD-1 | 001 | "Dev1" | Ch-1 | 01 | "Ch1" |
| DG-1 | 0001 | "DG01" | RFD/FFD-2 | 010 | "Dev2" | Ch-2 | 10 | "Ch2" |
| DG-2 | 0010 | "DG02" | RFD/FFD-3 | 011 | "Dev3" | Ch-3 | 11 | "Ch3" |
| DG-3 | 0011 | "DG03" | | | | Ch-4 | 00 | "Ch4" |
| | | | RFD/FFD-7 | 111 | "Dev7" | | | |
| DG-15 | 1111 | "DG15" | RFD/FFD-8 | 000 | "Dev8" | | | |

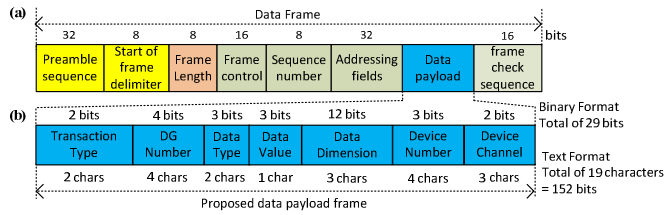


Fig. 4. (a) Standard Data Frame for ZigBee, (b) Proposed data payload structure for each parameter.

As an example, a voltage sensor connected to channel-2 of RFD-5 in DG-4 measures a voltage magnitude of 220 V. The data to be transmitted is coded as shown in Fig. 5. From this figure, it can be seen that the 220 V measurements can be transmitted by 26 bits when binary format is utilized or by 152 bits when text format is used.

By applying the above discussed data management, the number of data transmission in the MG is significantly reduced without causing any difficulty in MG normal operation.

IV. DATA TRANSMISSION DELAY

The time to transfer each bit by ZigBee devices depends on the data transfer rate. This time can be calculated as $T_{Bit} = 1/\text{data rate}$. Hence, T_{Bit} is equal to 4, 25 and 50 μs for the 2.45 GHz, 915 MHz and 868 MHz ZigBee devices, respectively.

The required time to transfer a symbol (T_{Symbol}) can be calculated as $T_{Symbol} = T_{Bit} \times \text{number of bits in each symbol}$. Hence, T_{Symbol} of 2.45 GHz ZigBee is $T_{Bit} \times 4 \text{ bits} = 16\mu\text{s}$; however, T_{Symbol} when using 915 MHz and 868 MHz ZigBees are respectively $T_{Bit} \times 1 \text{ bits} = 25\mu\text{s}$ and $T_{Bit} \times 1 \text{ bits} = 50\mu\text{s}$.

The total processing time for the data payload ($T_{DataPayload}$) is calculated as

$$T_{DataPayload} = T_{Symbol} \times \text{ceiling} \left(\frac{\text{number of binary digits}}{\text{number of bits in each symbol}} \right) \quad (2)$$

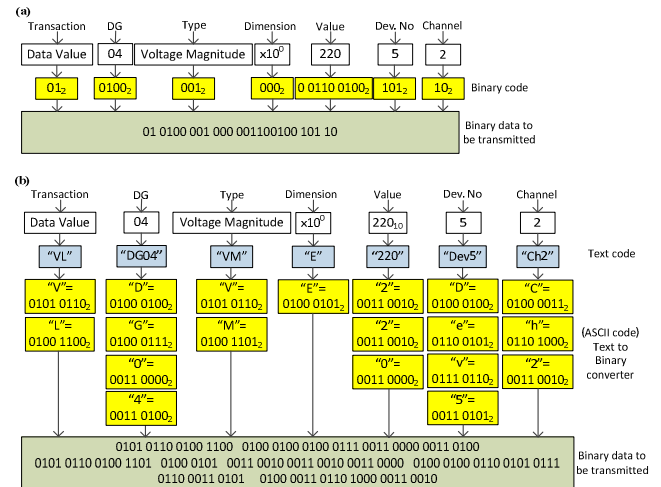


Fig. 5. An example illustrating how the output of a voltage sensor is coded within the data payload section of the ZigBee data frame based on (a) the proposed binary format, (b) the proposed text format.

where the number of bits for a symbol is 4 bits for 2.45 GHz ZigBee and one bit for 915 and 868 MHz ZigBees.

As an example, the processing time of transmitting the data payload of 220 V, shown in Fig. 5, for ZigBees with different carrier frequencies and different formats are listed in Table IV.

Assuming minimum number of bits is used for the address fields (i.e. 32 bits based on [17]), the total processing time for transferring the Data Frame ($T_{DataFrame}$) is calculated as:

$$T_{DataFrame} = T_{DataPayload} + T_{DF} \quad (3)$$

where T_{DF} is the processing time for the other sections of the Data Frame (i.e. preamble sequence, start of frame delimiter, frame length, frame length, frame control, sequence number, addressing field and frame check sequence sections). T_{DF} is 480, 3000 and 6000 μs respectively for 2.45 GHz, 915 and 868 MHz ZigBee.

After a successful data transaction, the receiving FFD sends an Acknowledgement Frame. The processing time of an ACK is 352, 2200 and 4400 μs respectively for 2.45 GHz, 915 and 868 MHz ZigBees.

The complete data transmission in ZigBee is started by transmitting the Data Frame by the transmitter followed by an Acknowledgement Frame received from the receiver. The receiver sends back the Acknowledgement Frame after a period of $12T_{Symbol}$. The waiting time since the data is fully transmitted until receiving the Acknowledgement Frame has a maximum of $54T_{Symbol}$ [17]. The successful data transmission in Zigbee is illustrated as shown in Fig. 6(a).

If the transmitter does not receive any an Acknowledgement Frame within this period, it resends the Data Frame to the receiver again. The transmitter will retry to transmit this data maximum of 3 times [18]. If the transmitter still does not receive an Acknowledgement Frame, it generates a MLME-COMM-STATUS indication with a status of NO_ACK [17]. The unsuccessful data transmission in Zigbee is illustrated as shown in Fig. 6(b).

V. NUMERICAL ANALYSIS RESULTS

The time delay for transmitting the numerical values of the measurements from sensors to the MG central controller or data commands from the central controller to the local controllers of each DG is of high importance in MG applications. In this paper, the time delay is calculated and presented as the processing time required to transfer a Data Frame ($T_{DataFrame}$). Fig. 7(a) shows the comparison of $T_{DataFrame}$ between 2.45 GHz, 915 and 868 MHz ZigBees for transferring one set of data (i.e. voltage magnitude, voltage angle, frequency, active power, reactive power and CB status) for different number of DGs in the MG. The results indicate that $T_{DataFrame}$ is up to around 48 and 86 ms respectively when using binary and text formats for 2.45 GHz ZigBee. However, when using 915 and 868 MHz ZigBee, $T_{DataFrame}$ becomes 5 and 10 times more than that of the 2.45 GHz ZigBee. From this figure, it can be seen that transmitting 15 sets of the above-mentioned data approximately takes 48.03 ms when using binary coding with 2.45 GHz Zigbee.

Fig. 7(b) shows the number of symbols required for transmitting the above-mentioned data when using 2.45 GHz, 915 and 868 MHz ZigBees. From this figure, it can be seen that the number of symbols required for transmitting 15 sets of the above-mentioned data when using a 868 MHz ZigBee and text format is very close to the maximum limit of ZigBee technology. However, the number of symbols when using 2.45 GHz and 915 MHz ZigBee in the same format is still respectively 5.5% and 34.8% of the maximum limit. Fig. 7(b) also shows the total symbols transmitted in MG is 1112 in binary format and almost 3 times more when using text format, for a 2.45 GHz ZigBee. This result indicates that when transmitting 15 sets of the above-mentioned data, ZigBee still has the capability to transfer approximately 56 times and 18 times more data respectively in binary and text formats.

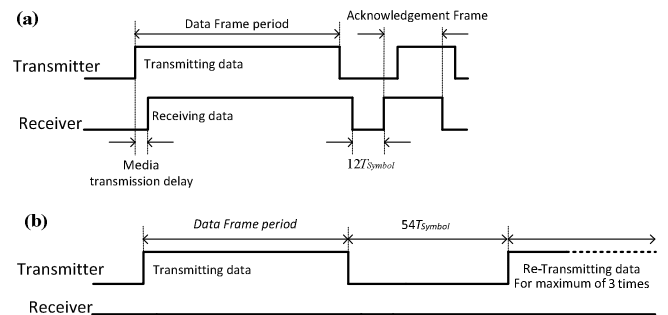


Fig. 6. Schematic representation of data transmission in ZigBee: (a) Successful data transaction, (b). unsuccessful data transaction.

Table IV

Numerical comparison of data processing time [ms] when using ZigBees with different carrier frequencies and different formats

| | Binary Format | Text Format |
|-------------------|---|--|
| 2.45 GHz | | |
| $T_{DataPayload}$ | $16\mu\text{s} \times \text{ceiling}(26/4) = 0.112$ | $16\mu\text{s} \times \text{ceiling}(152/4) = 0.608$ |
| 915 MHz | | |
| $T_{DataPayload}$ | $25\mu\text{s} \times 26 \text{ bits} = 0.65$ | $25\mu\text{s} \times 152 \text{ bits} = 3.8$ |
| 868 MHz | | |
| $T_{DataPayload}$ | $50\mu\text{s} \times 26 \text{ bits} = 1.3$ | $50\mu\text{s} \times 152 \text{ bits} = 7.6$ |

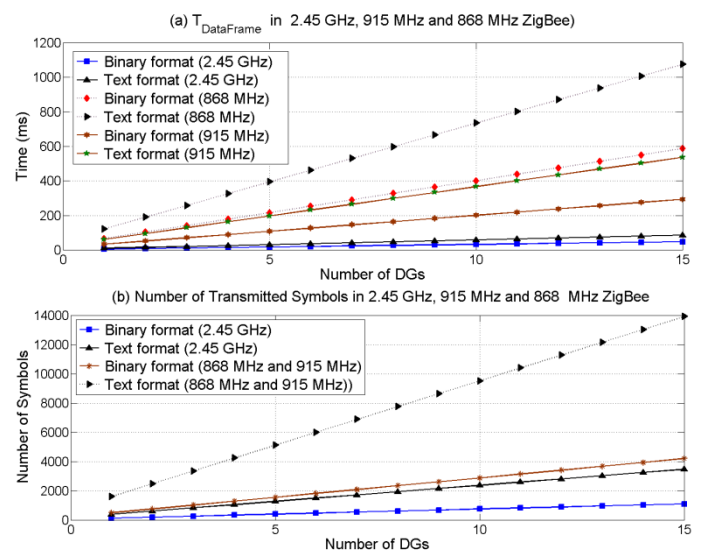


Fig. 7. Numerical analysis results.

VI. CONCLUSIONS

A ZigBee-based data payload coding for data communication is presented in this paper for future MGs. The proposed data communication is responsible for transmitting several electrical parameters (i.e. voltage magnitude, angle and frequency, active/reactive power and the CB status) from the local controller of every DG to the MG central controller as well as the reference for voltage magnitude and frequency and CB status from the central controller to the local controller of each DG. ZigBee standard Data Frame is utilized for transmitting the data while a new coding is presented for the data payload section of this frame. The new coding can represent each of the above-mentioned data, their values, dimensions and the origin of the data (sensor, meter, etc.) in binary or text formats. The selection of the binary/text format for the data payload and the carrier frequency effects the data

transmission delay. Through several numerical analyses, a comparison is provided on the expected data transmission delay as well as the maximum number of symbols used for the data transaction in MGs with several DG units. These analyses were carried out for the above-mentioned data sets and the relevant transmission delay was calculated in each format/coding configuration. From these analyses, it can be seen that to cover a vast area, ZigBees with carrier frequency of 868 or 915 MHz are required; however, the data transmission delay is increased while for shorter distances, a 2.45 GHz ZigBee can be used which has a much smaller data transmission delay.

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