Krzysztof MARCINEK[1,2]

Warsaw University of Technology, Institute of Microelectronics and Optoelectronics (1), Andra Sp. z o.o. (2)

Design and Implementation of ZigBee Solution for Last-Mile Problem in Automatic Meter Reading

Streszczenie. *Niniejsza praca przedstawia projekt zdalnej sieci odczytowej bazującej na technologii ZigBee. Motywacją realizacji opisywanego przedsięwzięcia jest wciąż nierozwiązany problem ostatniej mili w systemach zdalnego odczytu liczników energii elektrycznej. Główny nacisk w pracy położony został na kompatybilność i łatwość integracji z istniejącymi już instalacjami odczytowymi. Ważną kwestią jest także łatwość montażu i konfiguracji przy zachowaniu wysokiej sprawności sieci. Wyniki pracy zostały wdrożone w postaci instalacji testowej na jednym z osiedli w Warszawie. (**Projekt zdalnej sieci odczytowej bazującej na technologii ZigBee**)*

Abstract*. In this paper ZigBee wireless communication network design as an answer for last-mile problem in consumer Automatic Meter Reading (AMR) systems is described. The main stress was put on compatibility and integration with existing AMR networks along with installation complexity, which should be kept at the lowest possible level while maintaining low bit error rate (BER). Real-life implementation of ZigBee based energy meter reading in one of the modern estates in Warsaw is presented.*

Słowa kluczowe: AMR, AMI, ZigBee, smart grid
Keywords: AMR, AMI, ZigBee, smart grid

Introduction

With improving capabilities of networking, automation and information technology, automatic meter reading systems [1] and industrial sensor networks have been adapting various communication media for their purposes [2]. In Poland wireless data collection is mainly established using Global System for Mobile Communication (GSM) and specialized services such as Circuit Switched Data (CSD) or General Packet Radio Service (GPRS). In most cases, this scenario means that one GSM reading device is attached to every energy meter. In case of using CSD, the meter is identified by its phone number. While working in GPRS, the device most commonly acts as a data server, so it is convenient to have a fixed IP address of each device. This is realized by using private Access Point Names (APNs). Using separate GSM devices, with its own SIM card each, suits well industrial consumers due to their relatively small number in comparison with household consumers and their distribution over a very large area. In addition, the costs of GSM module and SIM card maintenance are insignificant within used energy costs.

As for small consumer market, the costs of installation and maintenance of automatic meter infrastructure should be matched to actual energy usage. Having very well prospering GSM AMR (Automatic Meter Reading) systems, it is a very natural idea to divide the costs over a larger number of consumers grouped in districts, estates or blocks of flats and utilize smart grid concept [3]. In this scenario one GSM device acts as a router or data collector for a number of meters identified by particular phone number or IP address. In some cases, when smart metering infrastructure is taken into account during area development and design stage, it is possible to connect energy meters with GSM module using wired technologies such as RS485 bus, current loop (CLO) or Local Area Network (LAN). However, in most cases if such solution is even possible, it generates significant costs related to integration with existing infrastructure. Local communication can also be easily realized using power line communication technology (PLC) [4]. PLC technology, especially based on FSK (Frequency Shift Keying) or BPSK (Binary Phase Shift Keying), is well known and widely used in many AMR systems but it suffers from very low data-rate (<2400 bps) and vulnerability to external environment. On the other hand, OFDM (Orthogonal Frequency Division Multiplexing) technologies are relatively expensive or range limited. Complex computation of number of channels simultaneously requires sophisticated processor requirements. Moreover, high power transceiver amplifiers are required to achieve sufficient range, what significantly increases device costs, size and power demands. IEEE 802.15.4 ZigBee [5, 6] is a new and proven wireless network technology with low cost and low power characteristics. With its speed of up to 250 Kbps and ranges from 50 m to even 1 km, depending on transmit power and urbanization rate, ZigBee is a candidate for another communication medium to be used interchangeably with others, depending on local area characteristics.

This paper is organized as follows. After related work consideration, AMR technology is briefly described. The next section presents design and implementation of ZigBee expansion board and ZigBee adapter to perform last mile local connection between energy meters. The following section presents ZigBee network installation and measurement results. The paper ends with conclusion and future work plans.

Fig. 1. Comander MULTIPORT GSM device with ZigBee expansion board

Related work

Over years many papers about adapting, implementing and improving ZigBee technology for Automatic Meter Reading have been published. One of the first approach was to use ZigBee to read data from mechanical energy meters and collect it using personal computer (PC).

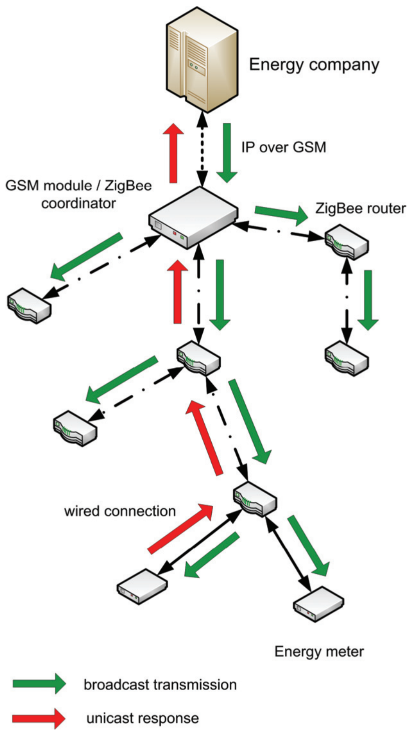

Fig. 2. GSM/ZigBee routing schema

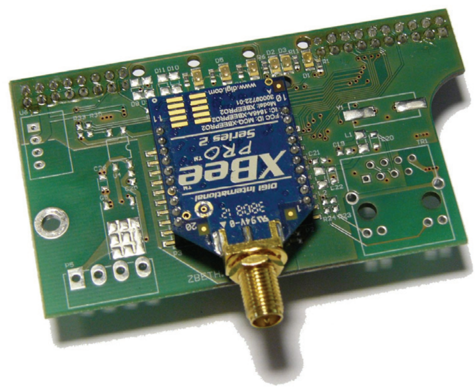

Fig. 3. ZigBee expansion board

Ethernet connection was used to further data distribution [7]. The next step was to replace PC with embedded data collector with incorporated wireless and ethernet modules [8]. The authors performed a set of performance tests but practical implementation is claimed as the future work. Hybrid Automatic Meter System using GSM technology is described in [9]. The designed system is still in prototyping stage and suitable only for energy meters with pulse output. Full design and practical implementation of ZigBee/GSM AMR is presented in [10]. Authors also introduced improved routing protocol. With additional power stage the designed system achieved 95% of packet delivery ratio. In comparison with related papers, this work extends the area of interests over compatibility with other existing ARM systems and describs various possible routing schemas. Installation issues, on-line network parameters monitoring and network maintenance are also described in example of the industrial practical implementation.

AMR Technology

This work is concentrated on energy meter reading. However, all the discussed problems and conclusions can be applied to other kinds of meter or sensor system where the end device or node have ability to communicate using wired interface. There are two main ways of collecting data from all kinds of meters. The first one is to perform a direct connection with particular device from the acquisition system. In this scenario GSM acts as a virtual wireless extension of physical meter interface enabling access to meter data to human operator or specialized intelligent software. The other possibility is to perform local data readout and buffer results in internal volatile or non-volatile memory. Collected data is then uploaded automatically or on demand to FTP or SMTP server. Both these methods have their advantages and inconveniences. The first one seems to be easier in real implementation. Nevertheless, in this case lots of parameters have to be taken into consideration. The first one is a communication standard. COSEM/DLMS [11] is a preferred standard to perform reliable connection over various transmission media, but most of energy meters use older IEC-62056 [12] standard. GSM latencies, possible data loss and packetization issues (such as packet size and timeout) have to be properly adjusted while configuring data collection program. GSM device and energy meter communication parameters are also responsible for reliable connection and lack of meter respond timeouts. The main advantage of this approach is system flexibility. Every change in a data readout schedule or internal registers supervision is performed only on the highest system level and there is no need to modify GSM device firmware or configuration. The system is also insensitive to communication protocol changes and offers full access to meter parameters. It also makes possible to have different meters with various protocols over the same network. On the other hand, buffered readout eliminates GSM communication issues reducing the number of configuration variables. The highest system level is responsible only for data processing and distribution. However, every schedule change in time or reading data demands configuration changes in collection device. The lack of real-time transparent connection makes it impossible to fast readout of data or internal parameters that are not supports by the firmware. Both reading schemes should be supported by GSM device in spite of their advantages and disadvantages.

ZigBee Implementation

Comander MULTIPORT (Fig. 1) is a highly configurable GSM device for transparent and buffered data collection and transmission from energy meters equipped with RS232, RS485 or CLO interface. The first step in designing ZigBee network was to utilize its free UART port available on expansion connector. ZigBee expansion board (Fig. 3) contains Xbee 802.15.4 module [13], power supply and indicator LEDs such as status LED or Received Strength Signal Indicator (RSSI). The main benefit of using Digi [14] devices is their on-module technology with on-board antenna connector. Such approach minimizes radio certification issues and shortens time-to-market factor. The manufacturer provides only 2.4 GHz ZigBee modules for now, but 868 MHz devices are soon to be released and designed expansion board allows for easily replacement of radio modules. Xbee module offers very sophisticated set of user commands and can be programmed with two alternative AT and API firmwares.The first one is suitable for transparent communication with local AT commands configuration. As the expansion board acts as network coordinator, full access to network resources is needed. Using API frames Xbee module can access, configure and communicate with every router and end device in the network.

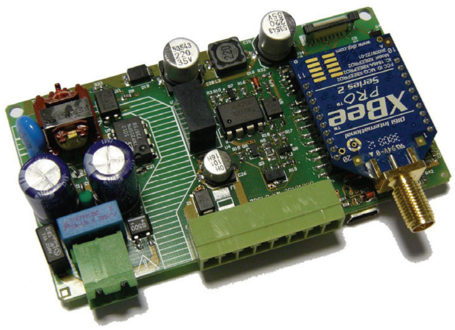

Fig. 4. ZigBee adapter board with CLO interface

Fig. 5. ZigBee CLO adapter

To setup basic network functionality several Comander MULTIPORT firmware patches had to be written. The first one is the API frame parser to encode and decode API frames according to the manual [14]. AT Command frames, used to set network ID, enable AES128 and write encryption key to local ZigBee module, and Remote AT Command Request frames are passed to the application layer. This provides access to every node in the network without interfering with existing Comander MULTIPORT firmware and configuration. Communication baud rate is implicitly set to 57600 bps. Much higher UART baud rate then communication link, which is usually set between 1200 to 9600 bps, ensures short time of frame collection and longer inter-frames time spaces to parse incoming frame. The other task was to write ZigBee communication driver. By using one of available Direct Memory Access (DMA) channels, all received characters are stored in specified memory space. After full frame reception, it is sent to appropriate application layer depending on the frame type. After receiving ZigBee Receive Packet frame, it is sent to GSM transmit FIFO while working in transparent mode or stored in internal memory while performing buffered readout. On the other hand, all the data sent with local communication port is encoded with ZigBee Transmit Request frames and sent to the module. Every Transmit Request Frame is followed by a Transmit Status frame from the Xbee module. This mechanism is used to ensure successful data delivery and perform retransmission if necessary.

ZigBee adapter (Figs. 4, 5) was designed as a standalone device with various interface options as RS232, RS485 or CLO and USB connection useful during configuration and installation process. Switch mode power supply (SMPS) with TNY255 integrated circuit enables wide range of AC and DC input voltages. Additionally, digital input and output are designed for future purposes and utilize smart grid concept. The unregulated and fused 10V output is designed to provide power supply for external devices, sensors or supply passive interfaces of energy meters. All interfaces and power outputs are galvanic isolated from the ZigBee module in case of installation or external devices failures. The default baud rate of energy meters is 9600 bps, however including ZigBee protocol overhead, multi-hop transmission and encryption/decryption complexity suggested baud rate for meter reading is 4800 bps or less. Transparent communication between ZigBee router and coordinator is available through AT firmware, so no additional application processor is required decreasing device hardware and software costs as long as its size. Network Watchdog Timeout is set to periodically check for the presence of network coordinator. Besides LED indication of network association, this feature is used for easy coordinator replacement. The first step is to prepare another coordinator with the same network ID and link encryption password as original network. The most probable scenario is that existing network and the new coordinator will work on different channel so they will not communicate. Nevertheless, after particular time of coordinator absence all remaining nodes will perform scan over all channels and join the new coordinator. Destination address for all modules is set to network coordinator address by default. Despite mesh topology and possible peer-to-peer connection, all communication is performed in tree-like structure, where packets are routed down the tree to the destination node and up to the coordinator.

The main task of this work was to provide transparent wireless ZigBee communication so no interference into existing data collection system is needed. Moreover, buffered transmission is handled by data collector so transparent communication between nodes is essential. To provide such solution a problem of data routing between particular nodes had to be solved. Each energy meter has unique identification number and responds only when receiving command containing that address. Another feature of energy meter system using IEC protocol is that great majority of data is sent from meter to concentrator. That is the reason why broadcast messages from coordinator to energy meters are used. Broadcasts are less reliable and energy efficient from unicast transmission but they can be retransmitted when necessary. Moreover, they are used only on the beginning of the transmission. Sent command travels to all routers and all energy meters as a result. Only the addressed energy meter will respond, so there is only the one router from which the coordinator will receive unicast data (Fig. 2). This solution ensures full compatibility with existing systems without ZigBee network as no knowledge about ZigBee routers and their addresses is necessary. Transparent functionality can be also extended over energy meters with variable communication baud rates or DLMS protocol. After the first response using start baud rate and broadcast address, received frame contains the address of ZigBee router that the particular energy meter is connected to. Concentrator can now use unicast Remote AT Command Request frame to change adapter speed, to adjust it to meter requirements, and continue communication only with addressed node. This mechanism can be used to create database of ZigBee modules existing in the network. List of energy meters connected to each module can be also easily recovered. Usage of such database is useful in further network extending, improving routing protocol and network maintenance. There are following three main routing protocols.

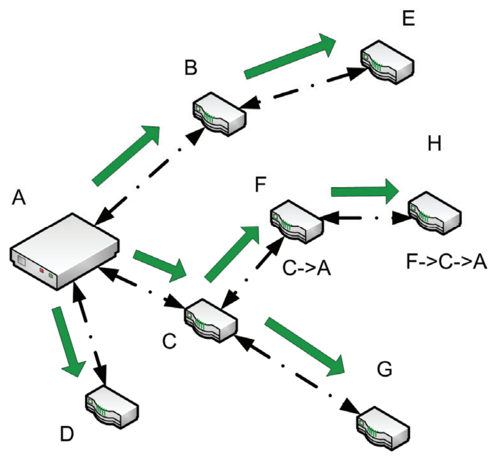

Fig. 6. Many-to-One broadcast packet

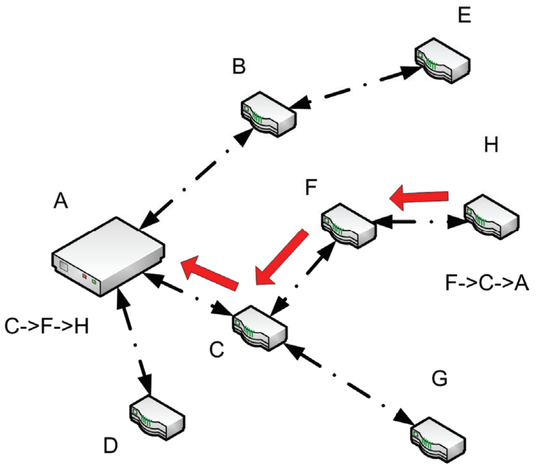

Fig. 7. Route Record transmission

AODV

Ad hoc On-demand Distance Vector (AODV) Mesh Routing is suitable for network not bigger than 40 nodes [14]. In this schema, each node stores the next hop address to reach the destination node. If there is no entry for particular node, route discovery must take place in order to find a communication path. Since only a limited number of routes can be stored on a module, route discovery will take place more often on a large network with communication between many different nodes and cause large packet overhead.

Many-to-one

In cases where many devices send data to a data collector Many-to-One routing protocol removes necessity of route discover. Setting Aggregate Routing Notification parameter in the data concentrator makes it to send periodical route request broadcast message transmission. While travelling through the network, each node appends its own address to that packet and retransmits it again. As the result, each node knows the exact path to the data concentrator (Fig. 6).

Source routing

Source Routing is the most complex routing schema, which can be exploited only by nodes with API firmware. It enables the full control of packet transmission route and is useful when a device such as data collector communicates with many nodes. After enabling Many-to-One routing by setting Aggregate Routing Notification, each data frame from a remote node is proceeded with Route Record Indicator frame, which contains addresses of all nodes participating in transmission (Fig. 7). Data collector should store all received Route Record Indicator frames in its own application space and use Create Source Route frame to send packet to particular node. This routing scheme is left for future work.

In described case, the first two methods are very similar. Using AODV will not cause route discover packets flood, because all nodes need to store routing path only to the coordinator. In this paper all route discover broadcast packets are replaced with data broadcasts, what eliminates the need for storing ZigBee node database and meter distribution over the network. Additionally when no network functionality apart from data transmission is needed, and all nodes in the network use the same baud rate, AODV and Many-to-One routing scheme can be achieved with ZigBee expansion board (Fig. 3) replaced with ZigBee adapter (Fig. 4) programmed with AT Coordinator firmware. Such a solution provides wireless network extension compatible with every GSM data collector having appropriate wired interface.

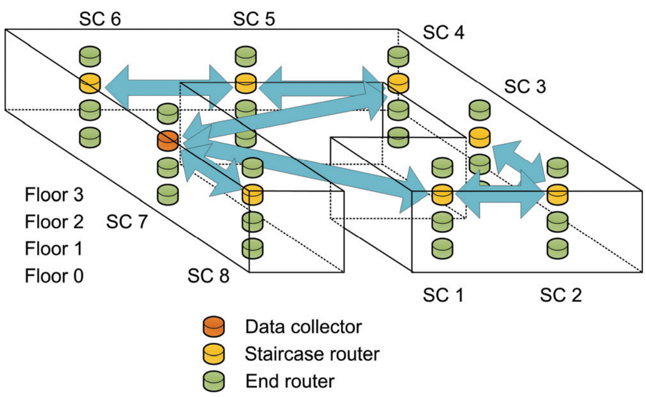

Fig.8. Established ZigBee network topology

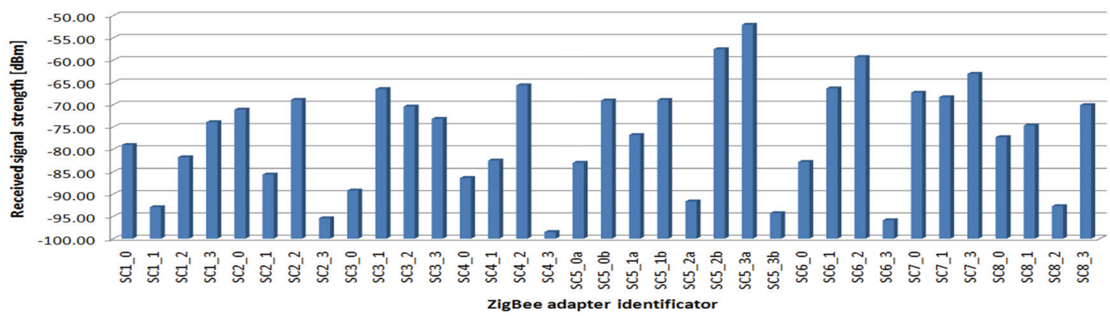

Fig. 9. ZigBee adapter average received signal strength

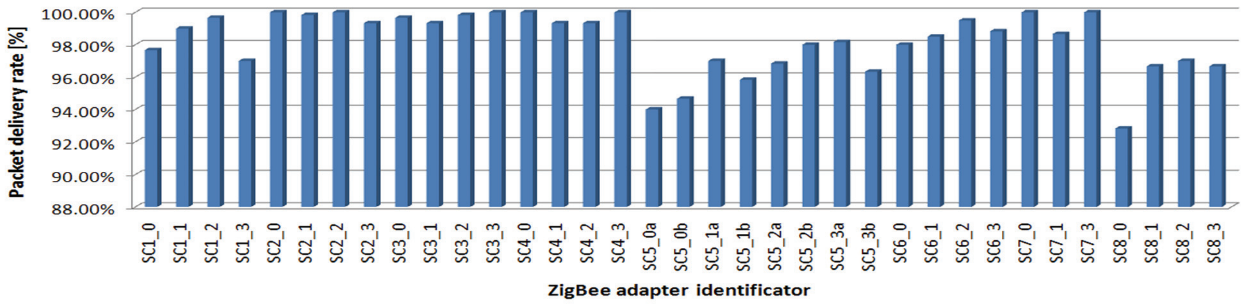

Fig. 10. ZigBee adapter packet delivery rate

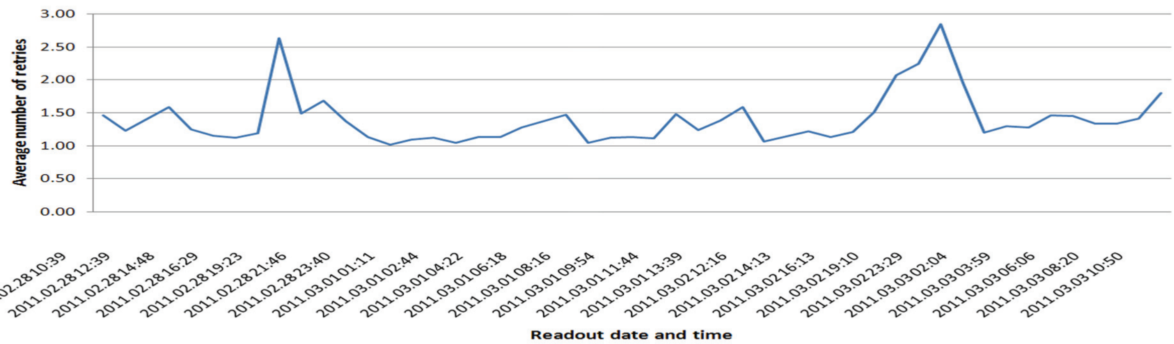

Fig. 11. Average energy meter readout retries over five day time

Installation results

Real-life implementation of described system was realized in one of the modern Warsaw estates consisting a block of ninety four flats. Thirty five ZigBee adapters are connected to from two to three Elster A220 energy meters with CLO interface and IEC protocol (Fig. 12) depending on the installation staircase (SC). The adapter CLO interface is capable of driving up to four devices. Most staircases have three energy meters on each floor, except fifth staircase with five metering points. This is a reason of having two adapters per floor in this particular staircase. One of the main disadvantages during installation process was the demand for all equipment to be hidden inside metal cases. The condition of no external components is very reasonable where fragile RF antennas are exposed to human factor. On the other hand, even modern construction industry is still not AMR friendly. Usage of metal energy meter cases is one of the examples. Unlike United States, European restrictions allow only +10 dBm (10 mW) of transmitting power on 2.4 Ghz. Together with metal covers, it strongly affects inter-adapter received signal strength. Dedicated PC software was prepared to evaluate adapter received signal strength, packet delivery rate and network topology thanks to XBee API frames and ZigBee Device Objects (ZDO) support [6]. After several test sets taking place in different week day and time, it was decided to place coordinator device in the seventh staircase on the second floor. Fig. 8 presents the distribution of ZigBee adapters over the block of flats. While establishing the network, each module seeks for the best quality place to join to. Each staircase created sub-network where one of the routers acts as a gateway to the direct connection to the coordinator or multi-hop transmission through other routers. For simplicity Fig. 8 shows only second floor adapter as staircase router. Fig. 9 presents average received signal strength of each module after two weeks period. Because of several adapters participating in communication, signal received strength from the particular node to the nearest router in the path is shown. Along with knowledge of network topology, this information can point communication bottlenecks. In general, one of the routers on each particular staircase has significantly lower received signal strength (SC1_1, SC2_3, SC3_0, ...). Reason for this is that routers participating in inter-staircase communication are separated by significantly larger distance and more difficult obstacles. Achieved results, where adapter received signal strength oscillates around minus 90 dBm, coincide with the results presented in [8], where measured received signal strength inside metal cover is minus 93.86 dBm. Even with such low receiving power, reliable connection can be established because of minus 102 dBm XBee receiver sensitivity.

Fig. 10 presents average packet delivery rate over the test period. Most of the adapters have over 98% efficiency of transmitted frames and the worst case is slightly below 93%. The system performed continuous readout of all energy meters in the network. Each transmission consisted of about 2 kB of data. As mentioned before ZigBee adapter have no application processor, and therefore no data buffering is possible. Along with IEC protocol, which provides checksum only after the whole data transmission, every packet error results in whole data readout failure. Despite of this inconvenience the average of one and a half retries falls on each energy meter over the test period. Fig. 11 presents only five day plot of network performance testing. Many papers about ZigBee and WiFi interference were presented over the years [15-17]. Nowadays existence of several WiFi networks in modern urban area is almost certain. During installation the average of six WiFi networks was in range in every metering node. Although using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and Direct Sequence Spread Spectrum (DSSS) interference immunity technique extensive load on nearby WiFi networks can influence ZigBee transmission. Fig. 11 shows two spikes of meter readout degradation. Both occur between seven PM and midnight, during after work household resident's activity. As to be predicted the best results were achieved late in the night and near the noon.

Fig. 12. Energy meter case with installed ZigBee adapters

Conclusion and future work

In this paper ZigBee wireless communication network design as an answer for last-mile problem in consumer AMR systems has been presented. Achieved results of 98% of delivered packet rate show, that this method can be successfully applied to the remote AMR systems. Presented solution provides both transparent and buffered communication independent to attached device protocol. Despite of using dedicated GSM modem with ZigBee integration board, possibility of using AT and API adapter firmware allows to integrate ZigBee communication into already existing AMR systems reducing both costs and installation time. Prepared PC software allows the system owner to remotely monitor network topology and transmission parameters along with modem parameters management extending its flexibility.

Future work will concern further system functionality improvements. Usage of module with on-board application processor and external memory will allow to implementing local buffered data readout and gaining independence from the radio link quality fluctuations or temporary inaction. Tests with 868 MHz modules are also planned. The only disadvantage of using this part of Industrial, Scientific and Medical (ISM) band is its 10% duty cycle limitation. On heavy network load, this regulation decreases the real RF data rate from 24 Kbps to 2400 bps what is over 100 times slower in comparison with 250 Kbps on 2.4 GHz band.

Acknowledgments

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***Authors**: Krzysztof Marcinek, Warsaw University of Technology, Institute of Microelectronics and Optoelectronics, ul. Koszykowa 75, 00-662 Warsaw, E-mail: K.Marcinek@imio.pw.edu.pl.*