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# A concept of measurement system based on the Z-Wave standard

***Abstract**. In the paper a new concept of measurement system based on the Z-Wave standard is presented. This standard is dedicated to use mainly in home automation systems, but its properties enable to use it in dispersed measurement systems and support wireless communication between measurement nodes in a mesh-type network. In the paper basic metrological aspects of the Z-Wave standard and an example of impedance measurement system are discussed.*

***Streszczenie.** W artykule zaprezentowano koncepcję systemu pomiarowego bazującego na standardzie Z-Wave. Standard ten dedykowany jest głównie do zastosowań w systemach automatyki domowej, posiada jednak właściwości pozwalające na wykorzystanie w rozproszonych systemach pomiarowych, umożliwiając bezprzewodową transmisję danych pomiędzy modułami pomiarowymi w sieci o strukturze typu mesh. W artykule omówione zostały podstawowe właściwości metrologiczne standardu Z-Wave oraz struktura przykładowego systemu do pomiaru impedancji. (**Koncepcja systemu pomiarowego opartego na standardzie Z-Wave**).*

**Keywords**: home automation systems, Z-Wave standard, impedance spectroscopy.
**Słowa kluczowe**: systemy automatyki domowej, standard Z-Wave, spektroskopia impedancyjna.

## Introduction

In a few recent years one can observe a growing interest in home automation systems based on the wireless data transmission standards (X10, ZigBee, Z-Wave, EnOcean, INSTEON) [1]. Among existing solutions the most widespread is the Z-Wave standard [2]. Typically, this standard is applied in remote monitoring and controlling devices in residential buildings. It can also be used in dispersed systems for remote measurement of different parameters, e.g.: in energy meters [3], or in impedance spectroscopy of objects either of considerable dimensions or installed in hard to access locations (bridges, poles) [4,5].

There are three major factors that predestine using the Z-Wave standard in dispersed measurement systems: the transmission range in the multi-hop mode of up to 150 m, the ease of implementation resulting from a simplified structure of the Open Systems Interconnection (OSI) model [6] and a high level of transmission security resulting from using 128-bit Advanced Encryption Standard (AES).

In the following chapters a brief description of the Z-Wave standard is presented and a few metrological aspects are pointed out. A concept of measurement system with Z-Wave modules is also discussed.

## The Z-Wave network structure

The Z-Wave standard enables wireless communication between nodes in a mesh-type network. Individual nodes can operate as controllers, routing-slaves or slaves. An example of network architecture containing different types of nodes is shown in Fig. 1.

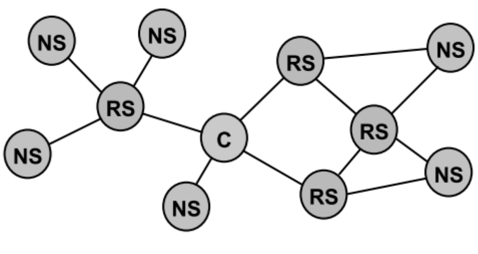


Fig.1. An example of typical Z-Wave network structure

The Controller (C) is the main node in the network and it is used to maintain communication capabilities. It can communicate with each node in the network if a route to that node exists. There can be more controllers in the network, but only one of them is the Primary Controller and is used to build the network by attaching new nodes.

All other nodes are slaves. There are two types of slaves: the normal and the routing ones. Normal Slave (NS) is a node, which does not know its neighbours and can only answer to requests from other nodes. Routing Slave (RS) is a node, which knows its neighbours and can initiate communication with other nodes.

## The General Layer Model

Communication in the Z-Wave network can be discussed basing on a four layer OSI model consisting of the radio, network, application and user interface layers (Fig. 2).

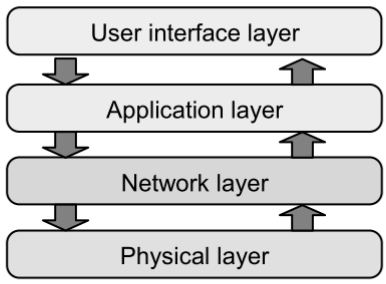


Fig.2. OSI model in the Z-Wave standard

The radio layer is responsible for transmitting bits and bytes of data from a transmitter to a receiver by means of modulating a carrier signal with the use of an encoding technique. It defines the carrier signal frequency, the encoding method, the speed of transmission and the hardware access.

The network layer is responsible for organization of the network by assigning individual identifiers to all nodes, defining routing algorithms that describe possible signal paths between nodes, and assuring reliable transmission of data between a source and a destination depending on retransmission of packets in the case of communication failure.

The application layer defines the meaning of data transmitted between nodes. Sequences of bytes are interpreted as commands or queries. The commands are used to change states of devices, whereas the queries are used to obtain information about devices or measured values.

The user interface defines how different pieces of information about the network are presented to the user and how the network can be controlled.

**The Radio Layer**

The Z-Wave uses license-free and regulated frequency bands. According to the multinational regulation issued by the CEPT organization the Z-Wave operates in the frequency range between 863 and 870 MHz. This band is applied to Short Range Devices (SRD 860).

The Frequency Shift Keying (FSK) modulation is used, which means that the logical states ’0’ and ’1’ are transmitted on two frequencies in the SRD 860 band.

Two encoding algorithms are used: Manchester for the data rate of 9.6 kbit/s and Non Return to Zero (NRZ) for the 40 kbit/s and 100 kbit/s data rates.

The Z-Wave network works with the peak transmission power of 10mW. This power level is only applied for 1 % of the time, which corresponds to an average radiation power of 0.1mW. Such a small radiation power limits the maximum distance between nodes to about 30 m [2], but it depends on many parameters:

a) the existence of obstacles between a transmitter and a receiver and the material of the obstacles;
b) screening caused by metal structures;
c) the penetration angle of radio waves passing different materials;
d) the type of antenna and coupling the antenna with the transceiver;
e) distances to other wireless signal sources.

If there are massive objects placed between a transmitter and a receiver the transmission range is limited to only a few meters. Otherwise, if a good external antenna with correct coupling with the transceiver is used, the distance in free sight can be extended to 200 m.

Furthermore, the Z-Wave standard enables the multi-hop transmission from a transmitter to a receiver through up to 4 intermediate nodes. Hence, the available distance between the most distant nodes can be increased to about 150 m. It enables to construct wireless measurement systems to diagnose objects with significant sizes.

The data frame in the radio layer is shown in Table 1.

It starts from the preamble used to synchronize a transmitter with a receiver. This is a bit pattern 01010101 that is repeated 10 times. After the preamble there is the Start of Frame Delimiter (SFD). Then data of size *k* from 12 to 64 bytes are transmitted. The frame is ended with the End of Frame Delimiter (EFD). The length of SFD and EFD delimiters is 1 byte each.

Table 1. The structure of data frame in the Radio Layer

| Preamble | SFD | Data | EFD |
|---|---|---|---|
| 10 | 1 | *k* | 1 |

The transmission time of a single frame depends on the data rate and the number of bytes in the data field of the frame, as is shown in Table 2.

Table 2. Transmission times of a single data frame

| Data size [B] | Frame size [B] | Data rate [ms] | | |
|---|---|---|---|---|
| | | 9.6 kbit/s | 40 kbit/s | 100 kbit/s |
| 12 | 24 | 20.0 | 4.8 | 1.9 |
| 64 | 76 | 63.3 | 15.2 | 6.1 |

The transmission time of a single frame for the lowest data rate is significant and may cause latency, especially in a more complex network with routing nodes. In the worst case scenario, when the data frame should be retransmitted four times to reach its final destination, the time between sending the data frame and receiving the response exceeds 0.5s.

**The Network Layer**

Each Z-Wave device has two identifiers: Home-ID and Node-ID. Home ID is a 4-byte constant for all devices in one Z-Wave network and is assigned to devices by the primary controller in a process called Inclusion. During that process the primary controller assigns also a unique 1-byte Node-ID to each device, which is used to distinguish devices in the network. A few Node-IDs are reserved for network organization procedures, hence the maximum number of devices in one Z-Wave network is 232, which is sufficient for measurement applications mentioned in the introduction. The data frame in the network layer is shown in Table 3.

Table 3. The structure of data frame in the Network Layer

| Home-ID | Node-ID Source | Frame Control | Length | Node-ID Destination | Data | Check Sum |
|---|---|---|---|---|---|---|
| 4 | 1 | 2 | 1 | 1 | *m* | 1 or 2 |

Each Z-wave data packet in the network is identified by its Home-ID and the Node-IDs of Source and Destination. The remaining fields, with exception of Data, are used to manage the packet itself and to control the flow of packets in the network.

There are three patterns of communication available: Singlecast, Broadcast and Multicast.

In the singlecast communication the data frame is transmitted from the source node to one destination node.

In the broadcast communication the same data frame is transmitted from the source node to all nodes in the network. The frame structure is the same as for the singlecast communication, but the Node-ID Destination field equals to 255, which is reserved for the broadcast communication.

In the multicast communication the data frame is transmitted from the source node to a set of nodes. The structure of data frame in that case is modified (Table 4).

Table 4. The structure of data frame for the multicast communication

| Home-ID | Node-ID Source | Frame Control | Length | Multicast Control | Multicast Bitmask | Data | Check Sum |
|---|---|---|---|---|---|---|---|
| 4 | 1 | 2 | 1 | 1 | 29 | *m* | 1 or 2 |

For the multicast communication addresses of nodes to which the data frame is to be transmitted are identified by bits in the Multicast Bitmask field. For the maximum of 232 devices present in the network this field occupies 29 bytes.

In the Z-Wave standard two Z-Wave networks can operate independently in close area, provided that they have different Home-IDs. In that case a lower data rate is achieved because communication is established on the same frequencies and transmission collisions can occur.

The Z-Wave network guarantees reliable communication. This is accomplished by an acknowledge message send from the destination node to the source node after successfully obtained the data frame previously sent from the source node to the destination node. The acknowledging messages do not apply to the broadcast communication. If a data frame is not acknowledged the source node retransmits it. After three unsuccessful attempts the source node reports a failure and an alternative way is selected.

The Z-Wave network is a mesh-type one, which means that the a data frame can be transmitted from the source to the destination via different routes. The number of possible routes depends on the network structure. An example of the network structure is shown in Fig. 3.

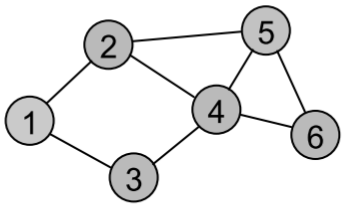


Fig.3. An example of network with possible connections between nodes

In the network presented in Fig. 3 there are 6 nodes, but not all nodes can communicate directly with each other, e.g. the node 1 can communicate directly with the nodes 2 and 3, but not with the node 5. These two nodes are called neighbours. In order to transmit a data frame from the node 1 to the node 5 we need a route, which consists of additional nodes working as routers. The Z-Wave network is able to route data frames via up to 4 repeating nodes using information included in the routing table (Table 5).

Table 5. The routing table with a selected route 1-3-4-5

| Node | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | | | | x | x | x |
| 2 | | | x | | | x |
| 3 | | x | | | x | x |
| 4 | x | | | | | |
| 5 | x | | x | | | |
| 6 | x | x | x | | | |

The routing table consists of information about neighbours (marked with the green colour) and enables to find a way from the source node to the destination node. In the Z-Wave standard it was defined that a route between a sender and a receiver can consist of up to 4 repeating nodes. Hence, for the given example there are following possible routes from the node 1 to the node 5 (from the shortest to the longest): 1-2-5, 1-2-4-5, 1-3-4-5, 1-2-4-6-5, 1-3-4-6-5 and 1-3-4-2-5. If communication via a selected route fails, the controller selects another possible route and repeats transmission. This procedure is repeated maximally three times and if transmission is still unsuccessful all selected routes are marked as failed. The routing decision is made prior to sending the data frame. This method is called the static source routing. It avoids rerouting attempts within the networks. Hence the power consumption by the network is decreased. Unfortunately, only mains-powered devices can operate as routers, so all above listed routes will be active only if the repeating nodes 2, 3, 4 and 6 are mains-powered.

**The measurement system architecture**

The general architecture of measurement system is shown in Fig. 4. It is composed of a USB Z-Stick Gen5 controller connected to a Personal Computer and several measurement units (nodes) with ZM5202 Z-Wave communication modules and sensors of different parameters. The controller enables to communicate with nodes and acquire the measured values via wireless transmission based on the Z-Wave standard. It is assumed that the node 4 is mains-powered, because it routes data frames between the controller and nodes 5 and 6. Other nodes can be battery-powered. They perform measurements initialized by the controller and there is no need to continuously supply power to these nodes.

Processing and analysing the acquired data is performed with the PC software. Hence, time consuming calculations are reduced and lifetimes of units are extended due to lower requirements. The measurement units 1, 2, 3, 5 and 6 can be placed in different and hard to access locations.

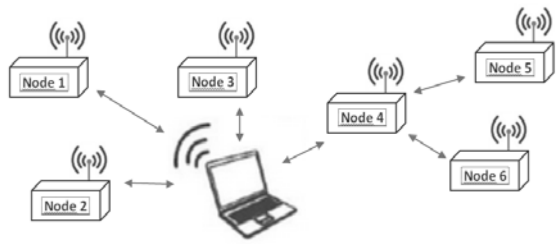


Fig.4. The measurement system architecture

One of the system applications can be monitoring an anticorrosion coating in different points of a steel construction of a bridge. For that purpose the measurement units should be equipped with miniaturized impedance analyser measurement units based on AD5933 Systems on a Chip (SoC) [7]. The PC software via the USB Z-Stick controller configures the measurement units, initializes measurement of the frequency characteristics and calculates the impedance spectrum of the anticorrosion coating.

**The ZM5202 Z-Wave module**

The ZM5202 module is composed of an SD3502 SoC with a built-in microcontroller and a Z-Wave transceiver, crystal and passive RF components (Fig. 5). It is manufactured in a small footprint of a size 12.5 mm x 13.6 mm (Fig. 6).

The key features of ZM5202 module are:

- 128kB Flash, 16 kB SRAM;
- 1000 step dimmer (TRIAC/FET);
- 4-channel 12-bit rail-to-rail ADC;
- 4-channel 16-bit PWM;
- 10 GPIOs;
- SPI and UART interfaces;
- Hardware implementation of 128-bit AES;
- Low sleep mode current of 1 μA;
- Power supply from 2.3 to 3.6V.

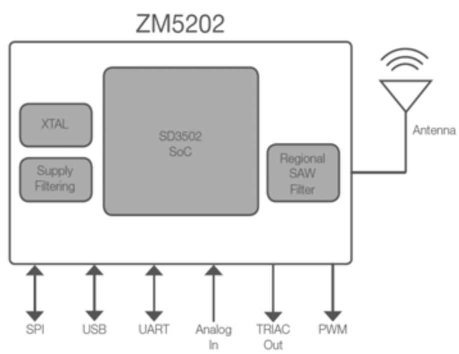


Fig.5. The internal architecture of ZM5202 Z-Wave module

Besides the very-low sleep current of the ZM5202 module, which is well suited for battery-powered devices, current consumption during reception and transmission equals, respectively, to $I_{RX}$ = 32 mA and $I_{TX}$ = 41 mA (with the maximum transmission power of 2 dBm). It can be seen that a special care should be taken for proper configuration of nodes and operation of the network in order to extend the batteries' lifetime.

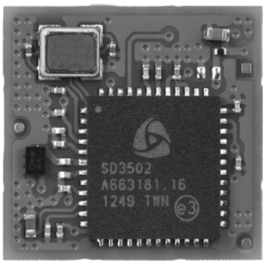

Fig.6. The ZM5202 Z-Wave module

**Operation of the system**

All nodes, with the exception of the node 4, in the measurement system shown in Fig. 4 are battery-powered. Hence, there is a need to take care of proper configuration of the system in order to assure powering for these nodes.

Slave devices in the Z-Wave network can operate in one of two modes:

a) as devices with wake-up intervals;
b) as Frequently Listening Routing Slaves (FLIRS).

In the first mode a node remains in the sleep state most of the time and a built-in clock wakes up this node regularly. After waking up the node sends a notification to the controller and process messages from the queue addressed to that node. A message can be a command or a request to perform a measurement and send the measurement results. If there is no message in the queue the node returns to the sleep state and waits until next wake-up time expires. The wake-up interval for the node can be configured freely. A shorter value will shorten the response time, but also decrease the battery lifetime. A longer value will delay communication with the node, but will preserve the battery power.

In the second mode a node also remains in the sleep state most of the time, but wakes up more frequently (e.g. every second) to check whether there is a signal transmitted on one of two frequencies used in FSK modulated communication. If there is no signal the node returns to the sleep mode and wakes up after the configured time. If a signal is detected, the node remains in the active mode and decodes a data frame to find out if this frame is addressed to that node. In order to wake up the node the controller needs to send a wake-up beam, which is a constant signal generated on one of two radio frequencies during time longer than the wake-up interval. An example of communication procedure between the controller and an FLIRS node is illustrated in Fig. 7. In this example the wake-up interval equals to 1 s and the wake-up beam duration - to 1.2 s.

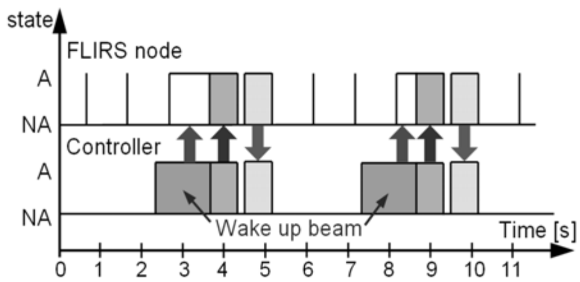


Fig.7. Communication between the controller and an FLIRS node

The waveforms shown in Fig. 7 inform whether a device is in the Active (A) or Not-Active (NA) state. Detection of the wake-up beam from the controller switches the node to the A state and enables to decode the data frame. If this is a query message the node can send a response message to the controller. After successful transmission the node switches again to the NA state and waits until next wake-up beam occurs.

In order to ensure fast reaction to commands send from the controller all nodes should operate as FLIRS devices. In that case the time delay during communication is minimized.

The general algorithm in the controller used to manage the systems is as follows:

a) Initialization of the controller;
b) Configuration of nodes as FLIRS devices;
c) Initialization of measurements by sending the broadcast message to all nodes;
d) Receiving measurement results from nodes;
e) Performing analysis of the acquired data in the controller and displaying the results.

**Conclusions**

Z-Wave is a widespread standard in home automation systems with an extension to user-configured measurement systems. Physical and network layers defined in the OSI model ensure reliable transmission of data frames between nodes. There is a capability to perform the multi-hop transmission from a transmitter to a receiver, which can significantly increase the distance between the most distant nodes to about 150 m. The presented module ZM5202 with the integrated transceiver can be used to perform wireless communication between the controller and nodes in the system dedicated to perform different measurements, e.g. in impedance spectroscopy. Nodes in the system can be battery-powered, because of low power consumption of the ZM5202 module and different modes of operation of slave devices defined in the Z-Wave standard. Unfortunately this does not apply to the routing slaves used in more complex network structures, which must continuously receive the radio signal.

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