XX IMEKO World Congress
Metrology for Green Growth
September 9–14, 2012, Busan, Republic of Korea

REMOTE MONITORING SYSTEM FOR IMPEDANCE SPECTROSCOPY USING WIRELESS SENSOR NETWORK

M. Kowalewski, *G. Lentka*

Faculty of Electronics, Telecommunications and Informatics, Gdansk University of Technology, Poland,
ul. G. Narutowicza 11/12, 80-233 Gdansk, mickowal@pg.gda.pl

Abstract: The architecture of a miniaturized impedance analyser with wireless communication module for remote Impedance Spectroscopy (IS) of anticorrosion coatings on difficult-to-reach objects (e.g. on the steel construction of the bridge) is described in this paper. Some practical aspects of implementation of a Wireless Sensor Network (WSN) are also discussed. A low scale, middle range, WSN network composed of a Base Station (BS) with a Personal Computer (PC) and nodes with impedance analysers fit with Atmel ZigBee modules was simulated in MATLAB. Effectiveness of different routing protocols in an ad-hoc WSN was studied.

Keywords: impedance spectroscopy, wireless sensor networks, ZigBee.

1. INTRODUCTION

Corrosion is a destructive process, which cause necessity of application of anticorrosion coatings on difficult-to-reach objects such as bridges, tanks, pipelines [1]. Due to economical and safety reasons there is a need to estimate state of an anticorrosion coating in order to determine a moment for the renovation. The most appropriate and accurate methods are based on Impedance Spectroscopy (IS) [2]. In these methods impedance analysers are used to obtain frequency characteristics of a coating in the form of a Bode or a Nyquist plots. The advantage of IS methods depends on non-invasiveness, ability of monitoring state of the coating in a whole its lifetime and also observation of formation and development of undercoating corrosion.

There is a lack of commercially available miniaturized impedance analysers able to perform IS directly in the field, where there are no power line sources, measurements must be performed simultaneously in many distant places and send to the PC for further processing. Battery-operation and wireless communication with the PC seems to be the most appropriate solution [3,4]. An architecture of a system for remote IS and principle of operation of an impedance analyser measurement unit is presented in this paper.

Important problem in remote acquisition of measurement results from impedance analysers depends on development, configuration and maintenance of a Wireless Sensor Network (WSN). In a past few years many aspects of usage of WSNs in distributed microsensor systems were considered. Research was concerned mainly on routing protocols optimisation in order to minimize power consumption of nodes and to extend WSN lifetime [5]. Only a part of research work assumes usage of a real transceiver modules, which have a set of configurable parameters only in a limited range [3]. In this paper we also simulate a WSN with ATZB-A24-UFL/U0 ZigBee wireless communication modules and analyse usefulness of different conventional routing protocols for remote IS.

2. SYSTEM ARCHITECTURE

The general architecture of a system is shown in Fig.1. It consists of a PC and several battery-powered impedance analyser measurement units placed in different points a steel construction of the bridge. All units in the system are equipped with wireless communication modules.

Fig. 1. The architecture of the system for remote IS.

The purpose of each measurement unit depends on performing measurements required for calculation of an impedance in a wide range of frequencies and evaluation of a state of an anticorrosion coating on the bridge. Due to difficult access to analysers, measurement results are send via wireless transmission to the PC. Communication between modules is performed in ZigBee standard due to low power consumption, flexibility of configuration and sufficient range of transmission [3]. Measurement units do not obtain impedance directly, but measure orthogonal components of two signals proportional to current and voltage on the measured impedance. Hence, time consuming calculations are reduced and lifetime of units are extended due to lower power demands. The most complex operations are performed by software in the PC. Its tasks depends on initialisation and configuration of measurement units with communication modules, general management of a WSN, acquisition of measurements, calculation of frequency characteristics and identification of parameters of equivalent electrical circuit used to model an anticorrosion coating.

2. IMPEDANCE ANALYSER MEASUREMENT UNIT

In construction of a measurement unit two Systems on a Chip (SoC) AD5933 were used [4]. This SoC contains analog and digital blocks required to determine orthogonal components of a signal on the basis of Digital Signal Processing (DSP) method. It is also fitted with I^2C interface used for control purposes and reading input registers. In the AD5933 one can distinguish two signal paths. The first one is used for generation of an excitation signal, while the second one is used for obtaining orthogonal components of a signal. Generation of a sinusoidal signal is performed by Direct Digital Synthesis (DDS) method. Signal path is composed of 27-bit DDS core, digital-to-analog converter (DAC) and amplifier A1 with programmable amplification and output resistance R_{out}. In the measurement path, signal from amplifier A2 is fed to the low-pass anti-aliasing filter and then sampled by 12-bit analog-to-digital converter (ADC). Calculation of real and imaginary part of a signal from acquired samples is performed in Discrete Fourier Transform (DFT) module.

Schematic diagram of a measurement unit of an impedance analyser is shown in Fig. 2. The first SoC is used for generation of an excitation signal $u_o(t)$ and obtaining orthogonal components of an $u_u(t)$ signal proportional to the voltage across the measured impedance Z_x. The second one is used to obtain real and imaginary parts of a $u_i(t)$ signal proportional to the current flowing through Z_x.

Extraction of $u_u(t)$ and $u_i(t)$ signals is performed in the input circuitry (amplifiers A4 and A5) connected with two SoCs. Voltage $u_x(t)$ across the measured impedance is measured with the differential amplifier A4 with gain equal to 1. Current $i_x(t)$ is measured with use of a current-to-voltage converter realised on the basis of amplifier A5. In order to provide measurements in a wide range of impedances, the current-to-voltage converter is required to operate with currents from 10 pA to 1 mA. In order to fulfil this requirement, a set of 8 range resistors R_R with values $10\,\Omega$, $100\,\Omega$, …, $100\,\mathrm{M}\Omega$ was used. These resistors are switched with use of miniature reed relays depending on magnitude of the measured impedance $|Z_x|$. In order to minimize phase shift introduced by amplifier A5 its magnification should be in the range $-0.01 < K \le -0.1$. Resistance R_o is switched simultaneously with the R_R ($R_o = 0.1\,R_R$) in order to limit current flowing through the current-to-voltage converter in case of a short of Z_x.

In order to operate in a wide range of frequencies from 0.01 Hz to 100 kHz, there is a need to use an external clock signal CLK fed into both SoCs. This signal is generated in the microcontroller in one of 6 frequencies: 8.192 MHz, 819.2 kHz, 81.92 kHz, 8.192 kHz, 819.2 Hz, 81.92 Hz and gives possibility to obtain 10 linearly spaced frequencies in each decade.

Approximation of an excitation sinusoidal signal $u_o(t)$ in DDS is performed with different number of samples. In a prototype of the constructed analyser this number changes from 2048 (for the lowest) to 22 (for the highest frequency). A disadvantageous effect occurs by using this signal, which depends on differentiation of stairs of that signal (amplifier A5 with resistor R_R in the loop and Z_x on the input acts as a differential circuit). In order to minimise distortions an SoC's internal Low Pass Filter (LPF) with different programmed limit frequency in each decade is used.

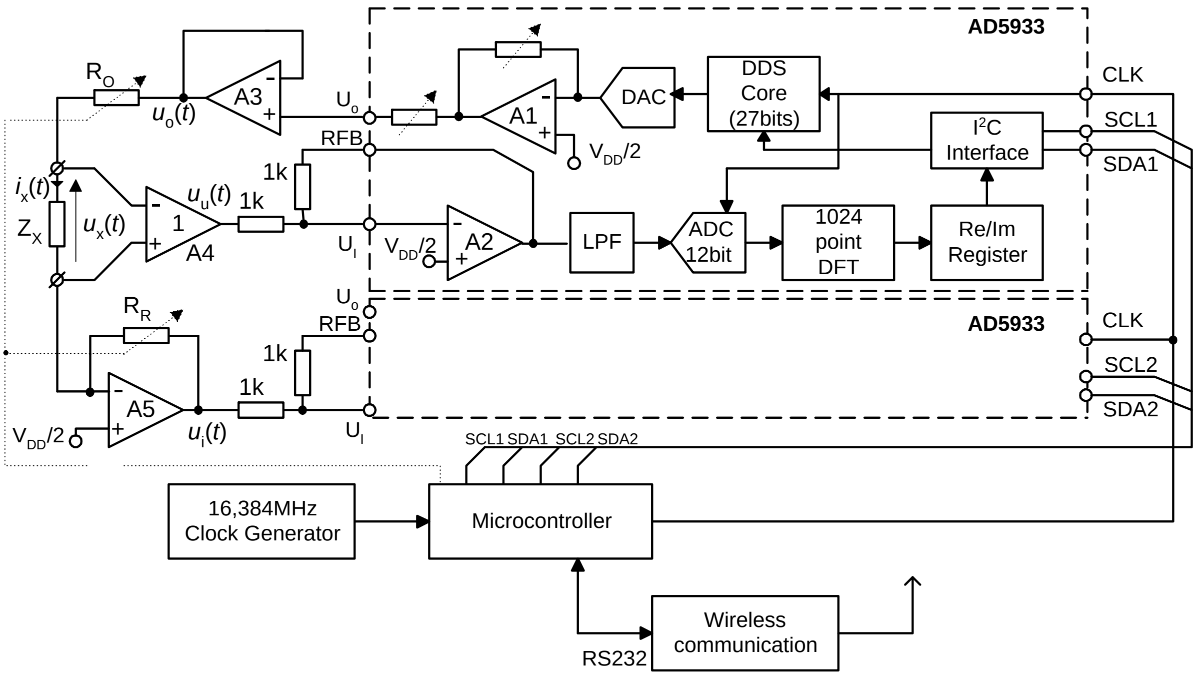

Fig. 2. Schematic diagram of the measurement unit of the impedance analyser.

Amplifiers A2 in both SoCs operate with magnification equal to –1. This result was achieved by attaching external 1 kΩ resistors.

Finally, an impedance of the anticorrosion coating is evaluated in the PC with the following equations [4]:

$$|Z_x| = \sqrt{\frac{(\mathrm{Re}U_u)^2 + (\mathrm{Im}U_u)^2}{(\mathrm{Re}U_i)^2 + (\mathrm{Im}U_i)^2}} R_R , \quad (1)$$

$$\varphi_{z_x} = arctg\frac{\mathrm{Im}U_u}{\mathrm{Re}U_u} - arctg\frac{\mathrm{Im}U_i}{\mathrm{Re}U_i} , \quad (2)$$

where: R_R - range resistance of the current-to-voltage converter, ReU_u, ImU_u, ReU_i, ImU_i - orthogonal components of signals u_u(t) and $u_i(t)$ read from registers of SoCs.

2. RADIO MODEL IN ZIGBEE WSN

Information about orthogonal components of signals u_u(t) and $u_i(t)$ from each measurement unit needs to be send to the PC via wireless transmission. An appropriate routing algorithm in WSN must be implemented to this aim.

Most WSN routing algorithms assume a simple first order radio model of a node (Fig. 3). In that model E_{elec} [nJ/bit] is an amount of energy consumed by radio electronics circuitry and e_{amp} [pJ/bit/m^2] is a transmit amplifier power consumption. It is assumed that transmitter power level is ideally adjusted to the distance d to the receiver, which is not possible to reach in practise. Hence, we propose to adapt the 1st order radio model to ATZB-A24-UFL/U0 ZigBee modules of Atmel and use it in simulations.

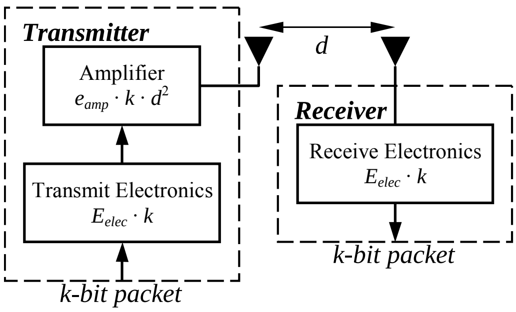

Fig. 3. First order radio model.

In these modules transmitter output power P_{out} is adjusted in 16 steps in the range from 10 dBm to 20 dBm [6]. Relation between P_{out} and module current consumption I_{tx}, shown in Fig. 4, was evaluated on the basis of the specification of AT86RF230 transceiver used in ATZB-A24-UFL/U0.

For a supply voltage V_{cc} = 3 V, current consumption in TX mode I_{tx} and a maximum on-air data rate of the module (250 kbit/s), we can obtained power consumption as:

$$E_{tx}\,[\mathrm{nJ/bit}] = V_{cc}\,[\mathrm{V}] \cdot I_{tx}\,[\mathrm{mA}] / 250\,[\mathrm{kbit/s}] \cdot 10^{-6}, \quad (3)$$

which changes from 346 to 600 nJ/bit, depending on P_{out} value set in the module.

Next we considered how to set P_{out} to assure connection between nodes in the WSN.

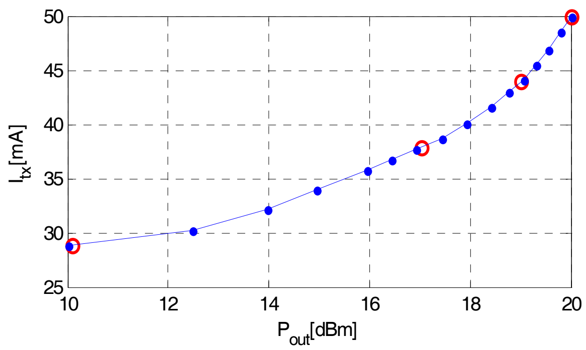

Fig. 4. Relation between transmitter output power and current consumption for ATZB-A24-UFL/U0 module.

Generally, received power level at receiver input S_i in dBm can be obtained from equation [7]:

$$S_i\,[\mathrm{dB}] = P_{out} - C_t + G_t - P_l + G_r - C_r, \quad (4)$$

where: P_{out} [dBm] - output power of transmitter, C_t, C_r [dB] - transmitter, receiver cable attenuation, G_t, G_r [dBi] - transmitting, receiving antenna gain, P_l [dB] - path loss. Usage of ideal cables and isotropic antennas was assumed, hence $C_t = C_r = 0$ dB and $G_t = G_r = 0$ dBi. In order to assure correct transmission even in very bad conditions (obstructions, fog, etc.), it was assumed that received power levels at BS and all nodes should not be less than $S_i = S_{min} + 50$ dB = – 54 dB, where S_{min} = – 104 dBm is the receiver sensitivity [6]. A following formula describing path loss P_l between two isotropic antennas in free space was used to obtain required output power of a transmitter [7]:

$$P_l = 20\log_{10}\left(4\pi d \lambda^{-1}\right), \quad (5)$$

where λ = 12.5 cm is the wavelength for 2.4 GHz ZigBee radio band and d is a distance between antennas. On the basis of (1) we also calculated module power consumption in RX mode, which is constant and equals E_{rx} = 276 nJ/bit.

3. WSN SIMULATION

An ad-hoc WSN with BS and nodes composed of impedance measurement units shown in Fig. 2 and ATZB-A24-UFL/U0 ZigBee communication modules was simulated. Nodes were localized in 15 different places of a steel construction of a 100 m long bridge shown in Fig. 5.

It was assumed that each node is equipped with 3 V battery cell with capacity Q = 1 Ah and that BS is powered from unlimited power source. Furthermore, it was assumed that a size of a data packet, which contains information about orthogonal components of measured signals u_u(t) and $u_i(t)$ equals 8 kbit. Nodes do not perform data aggregation, because the system operator is interested to acquire measurements independently from each node and process them in the BS by a dedicated software. Power consumption of measurement units was omitted, since these devices evenly discharges battery cells of all nodes and do not influence on work specificity of routing protocols.

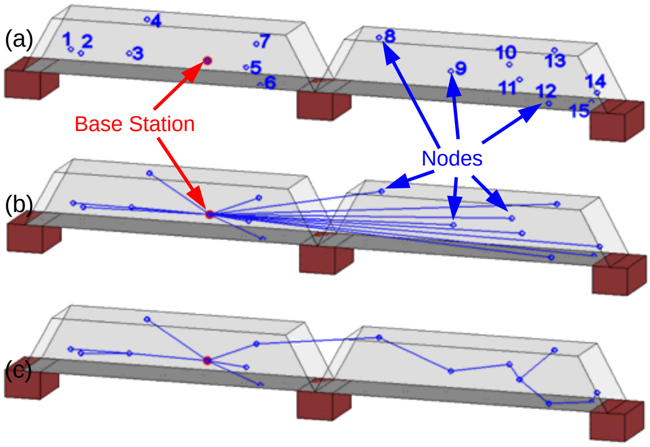

Fig. 5. Placement of nodes on walls of a bridge (a). Connections between BS and nodes in direct (b) and multi-hop (c) transmission.

Two routing protocols with direct and multi-hop transmission were compared. In the direct communication protocol each node transmits data packets directly to the BS and energy required for transmission grows for nodes placed further from the BS. However in the multi-hop transmission data packets are send to the BS through intermediate nodes in order to decrease energy-expensive transmissions on long distances. In this protocol the intermediate nodes are chosen such that the transmit amplifier energy is minimized, hence the protocol is named in the literature as a Minimum Transfer Energy (MTE) routing protocol [5].

Performed simulations point that both protocols consume power of nodes in a very diverse way. In the direct transmission power consumption is greater for nodes placed further from BS, but do not rise for nodes with numbers greater than 10, because power loss obtained from (5) is to high to guarantee the minimum value of S_i (Fig. 6). Hence, these nodes must transmit with a maximum power of 20 dBm.

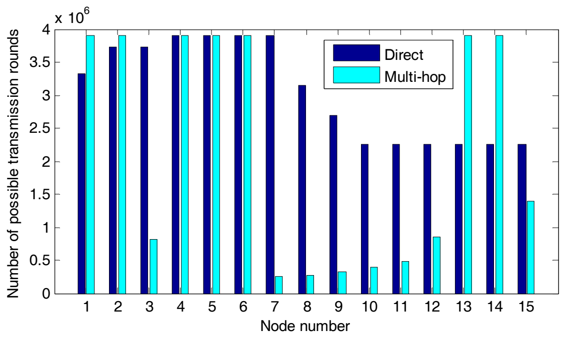

Fig. 6. Number of possible transmission rounds in WSN for two routing protocols with direct and multi-hop transmission.

However in the multi-hop transmission considerably more energy is dissipated by nodes localized near BS, if they are placed in sub-tree with a high depth. It is caused by necessity of passing on data packets from nodes localized deeper in the tree structure. These nodes are subject to exhaustion of battery cells most of all, eg. the most loaded node with No. 7 must receive 8 and transmit 9 packets in each round of transmission, while nodes 1, 2, 4, 5, 6, 13 and 14 are required to transmit only one packet in each round.

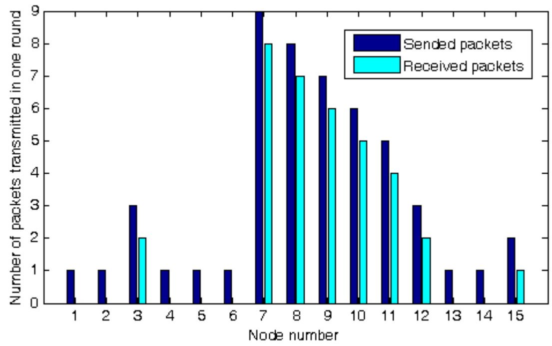

Fig. 7. Number of packets transmitted in one round in multi-hop transmission.

4. CONCLUSIONS

The miniaturized battery-powered impedance analyzer with measurement unit equipped with two SoCs AD5933 enables to obtain impedance frequency characteristics of an anticorrosion coating in difficult-to-reach places eg. on bridges, hence allowing to determine the best moment for the renovation. Fitting of the measurement unit with the wireless communication module eliminates necessity of usage of costly wiring and effectively increases ability to reconfigure structure of the system.

Two conventional routing protocols were simulated in an ad-hoc WSN composed of the BS and 15 ATZB-A24-UFL/U0 Atmel ZigBee modules. Preliminary research performed with assumption of on the enhanced 1st order radio model adapted to these modules shown that routing protocols with direct and multi-hop transmission, despite significant differences, are sufficient for remotely acquiring data from impedance measurement units.

5. REFERENCES

[1] F. Deflorian, S. Rossi, L. Fedrizzi, P. Bonora, "The application of electrochemical impedance spectroscopy for studying the mechanism of corrosion protection by organic coating", Proc. of the Third Int. Conf. on Electrochemistry ISE III Luxor, Egypt, Vol. 1, pp. 29-30, 2001.

[2] E. Barsoukov, J. Macdonald, "Impedance Spectroscopy: Theory, Experiment and Applications", J.Willey&Sons, 2005.

[3] J. Hoja, G. Lentka, P. Rolbiecki, "Distributed impedance spectroscopy system", Przegląd Elektrotechniczny, R. 87, No. 9a, pp. 20-23, 2011, (article in Polish language).

[4] J. Hoja, G. Lentka, "System for wireless monitoring of quality of anticorrosion coatings on the objects difficult-to-reach", Pomiary Automatyka Kontrola, Vol. 56, pp. 1100-1103, 2010, (article in Polish language).

[5] W. R. Heinzelman, A. Chandrakasan, H. Balakrishnan, "Energy-Efficient Communication Protocol for Wireless Microsensor Networks", Proc. of the 33rd Hawaii Int. Conf. on System Sciences, pp. 1-10, 2000.

[6] Datasheet of ATZB-A24-UFL/U0 module www.atmel.com/dyn/resources/prod_documents/doc8228.pdf

[7] M. F. Iskander, Z. Yun, "Propagation Prediction Models for Wireless Communication Systems", IEEE Transactions on Microwave Theory and Techniques, Vol. 50, No. 3, pp. 662-273, 2002.