Design of Ultra-Low-Energy Temperature and Humidity Sensor Based on nRF24 Wireless Technology

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***Abstract*—The proposed article introduces a low-cost and ultra-low-energy wireless sensor design that forms part of a wireless network consisting of one central node and several peripheral sensor nodes. The nRF24L01+ transceiver modules operating in unlicensed 2.4 GHz band are used as a wireless technology. The main effort is focused on the optimal selection of wireless communication parameters to ensure reliability and data transmission range between central and sensor nodes. In addition, a design and implementation of wireless sensor node to monitor humidity and temperature environmental data is discussed. A conducted series of experiments to assess the power efficiency and communication reliability have shown that the proposed wireless sensor network is suitable for Smart Home applications. Developed sensor node's transmission power is approx. 3.5 mA, operating up to 225 days in standby mode while driving a single coin battery.**

***Keywords*—humidity; low-cost; nRF24L01+; temperature; ultra-low-energy; wireless sensor network**

I. Introduction

Wireless Sensor Network (WSN) is an emerging technology that is being deployed to capture and collect different environmental or physical conditions such as temperature, pressure, motion, light, etc. for a wide range of applications. Basically, WSN is a distributed network formed by a large number of sensor nodes with a sensing and computing device, radio transceivers and power components for each node. [1], [2]. WSNs feature easier deployment and reconfiguration capabilities compared to wired networks. However, they have limited processing and computational speed, storage capacity, communication bandwidth, and power supply. Nevertheless, due to the rapid development of sensor technologies and advances in wireless communications, WSN is the key component for applications such as Smart Homes, Home Care Systems, Ambient Assisted Living Systems or Internet of Things (IoT). In particular, these fields of application have become an attractive research topic due to a growing interest in remote monitoring of elderly people and the sensing of their home environment [3], [4], [5]. These multivariate data provide notification or decision results as a fusion of environmental and human-related data to enhance living comfort and prevent hazardous situations, thereby increasing their quality of life. Examples include a temperature, motion, gas sensor in each room or a combination of cardiovascular and blood pressure sensors carried by a human [6], [7], [8], [9]. Like any other wireless communication technology, WSNs also have concerns about energy efficiency, reliability, cost and form factor that should be considered and discussed further in the design stage.

For temperature and humidity monitoring, a low-cost and ultra-low-energy WSN system using the 2.4 GHz radio band is developed and implemented in this paper. Our design is based on Nordic Semiconductor's low-energy RF module. A central WNS node was developed as well as a peripheral sensor node. Subsequently, a series of experiments to evaluate the power efficiency and reliability of communication were conducted in a real-life environment.

II. Materials and Methods

There are generally many types of wireless modules available on the market, usually operating in the unlicensed radio bands of industry, science, and medicine (ISM). Among the most popular modules are technologies such as Bluetooth, Zigbee, Wi-Fi and so on. They differ in carrier frequency, range, data transmission rate, energy consumption, price and last but not least form factor [10]. Based on the application requirements, these parameters should be specified before the WSN design. Our effort is focused on the WSN design for Smart Home applications, so the wireless module range should allow average size three-bedroom flat or one-story house area to be covered. We considered sensor node to work in notification operational mode rather than in mode of data stream. The maximum rate of data transmission was therefore not considered to be a crucial parameter of the wireless module. However, because of the fact that the sensor node is driven by battery, the most essential parameters of the wireless module are small size, low price and ultra-low energy consumption.

As a result of the above requirements, the integrated circuit module nRF24L01+ transceiver driven by the lithium coin cell battery was used. In our design, we considered using only one central WSN node capable of either receiving data from multiple sensor nodes or transmitting data to multiple sensor nodes. Thus, the topology of the star network was used. There are many different types of analog and digital sensors that can be integrated into the WSN sensor node. We decided to use the developed temperature and humidity sensors to demonstrate low-cost and ultra-low-energy WSN. The block diagram of designed WPS central node and sensor node is depicted in Fig. 1. The implementation of each individual WPS component such as temperature and humidity sensor, wireless communication parameters and central node configuration is discussed separately in the following subsections.

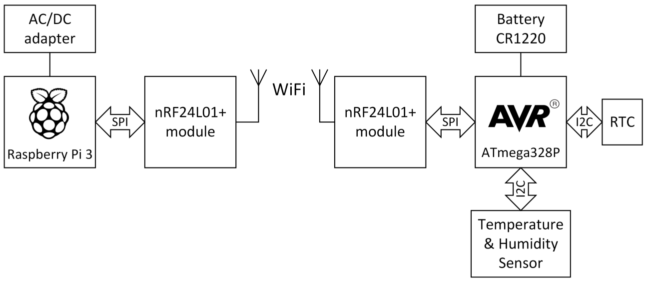

Fig. 1. The block diagram of WNS central and sensor node utilizing nRF24L01+ modules for wireless communication.

A. Temperature and Humidity Sensor Node

The sensor node comprises four basic electronic components: a humidity and temperature sensor, a real-time clock (RTC), a microcontroller (MCU) and nRF24L01+ wireless module. The HTU21D is used as a relative humidity and temperature sensor. It communicates with MCU via digital 2-wire interface (I2C) at 100 kHz. A relative humidity data is measured with accuracy of ± 2 % with 12-bit resolution. The humidity measuring time is typically 14 milliseconds. A temperature is red from the sensor with the accuracy of $\pm$ 0.3 °C and 14-bit resolution. The temperature measuring time is typically 44 milliseconds. It can operate at supply voltage from 1.5 V to 3.6 V. The typical current consumption values are declared in the datasheet as 450 μA and 0.02 μA while measuring and in sleep mode, respectively. [11]

The RTC is used for waking-up the MCU in predefined periods, e.g. every minute. The DS3231 chip is used as a extremely accurate RTC which incorporates I2C interface. [12] It includes an integrated temperature-compensated crystal oscillator with accuracy $\pm$3.5 ppm in the temperature range from -40 °C to +85 °C. It can operate at supply voltage from 2.3 V to 5.2 V. The RTC contains a battery-backup input for the continuous timekeeping. A maximal active supply current at main voltage 3.63 V is 200 μA, and 110 μA when I2C bus is inactive (stand-by mode). When the main voltage supply is missing, the RTC is fed up from a back-up battery. The battery current at 3.63 V is maximal 70 μA and typically 0.84 μA in active and time-keeping mode, respectively. So, powering the device from battery-backup input is more power-saving option, and therefore it is used in proposed solution.

The next element of the sensor node is the wireless module nRF24L01+ with PCB antenna (Fig. 2). The wireless module

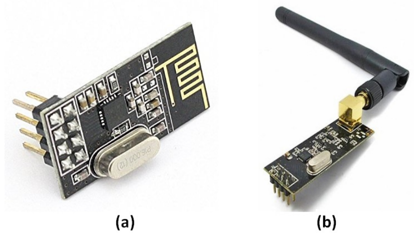

Fig. 2. The nRF24L01+ module with PCB (a) and external antenna (b).

is ultra-low power (14 mA in a peak) transceiver operating at the carrier frequency of 2.4 GHz. Determined by the module operation mode, it consumes only 900 nA and 26 μA in power-down and standby mode, respectively. The start-up time is up to 1.5 ms from power-down mode and 130 μs from standby mode. The nRF24L01+ supports three air data rates: 250 kbps, 1 Mbps or 2 Mbps. The transmitter has programmable output power: 0, -6, -12 or -18 dBm. The receiver has integrated channel filters with the different sensitivity settings according to the data rate: -82 dBm (at 2 Mbps), -85 dBm (at 1 Mbps) and -94 dBm (at 250 kbps). The transceiver operating voltage is from 1.9 V to 3.6 V. The nRF24L01+ is controlled and configured through a 4-pin Serial Peripheral Interface (SPI). [13]

The next element of the sensor node, the MCU ATmega328P was used as a "heart" of sensor node. It operates at lowest frequency (1 MHz) controlled by the internal RC oscillator in order to minimize its power consumption. According to the datasheet, the ATmega328P at 1 MHz clock has a current consumption of about 400 μA and 4 μA in active and power-down mode, respectively. [14]. Therefore, the MCU is kept in power-down mode all the time, except of the periods when the humidity and temperature data are acquired, and the data are wirelessly sent to the central node. A waking-up procedure of the MCU is regularly provided by external interrupt from the RTC device every minute. The flowchart of developed MCU firmware is depicted in Fig. 3. The firmware starts right after the battery is inserted.

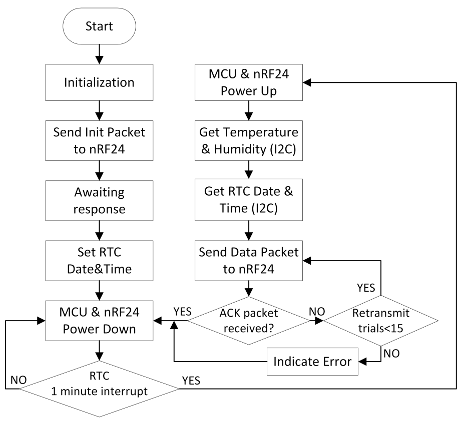

Fig. 3. The flowchart of the developed MCU firmware.

The common power source such as a coin cell battery can power all electronic components of the developed sensor node. The lithium CR1220 battery was chosen due to its parameters such as small compact size (12.5 mm in diameter, thickness of 2 mm), a nominal voltage of 3 V, and a capacity of 40 mAh. The hardware prototype of sensor node is shown in Fig. 4. All electronic components are placed on two-sided PCB with width of 35 mm and height of 30 mm. The MCU is not visible in Fig. 4 because it is placed under the nRF24L01+ module. The humidity and temperature sensor HTU21D was implemented in a form of PCB adapter (blue in Fig. 4), therefore it was easy to solder it to the rest of the circuitry. The LED indicates active state of state of sensor node.

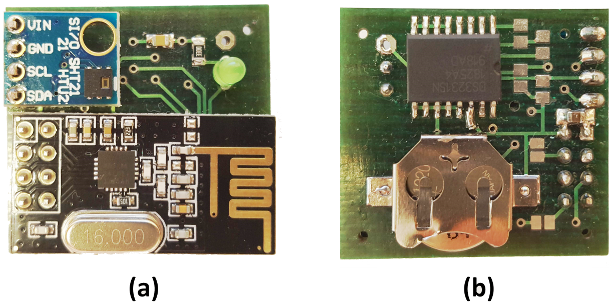

Fig. 4. The PCB of the sensor node prototype. A nRF24L01+ and HTU21D PCB side (a) and battery and RTC PCB side (b).

B. Central node

As a computing device of WSN central node, the Raspberry Pi 3 has been chosen. The Raspberry Pi 3 is a single-board computer equipped with Quad Core 1.2 GHz 64-bit CPU, 1 GB RAM, LAN, 4x USB port, integrated Wi-Fi, Bluetooth Low Energy (BLE), and 40-pin extended GPIO. The Raspberry Pi 3 is running Linux based operating system named Raspbian. The central unit collects data from all sensor nodes and provides information about sensor status in appropriate form, e.g. web-page accessible from the internet. The wireless module nRF24L01+ is connected to GPIO header of Raspberry Pi through the SPI interface (Fig. 5). The wireless communication properties are set according to the Table I in the initialization program phase. The program for maintaining communication between the communication module and the Raspberry Pi is written in Python scripting language. The flowchart of the program is shown in Fig. 6.

TABLE I. THE WSN WIRELESS COMMUNICATION PARAMETERS

Parameter	Value
Carrier Frequency	2.508 GHz
Transmitter Power	0 dBm (1 mW)
Data Rate	250 kbps
CRC bytes	2
Auto Acknowledgment	Yes
Auto Retransmit	Yes
Auto Retransmit Trials	15
Auto Retransmit Delay	1250 µs

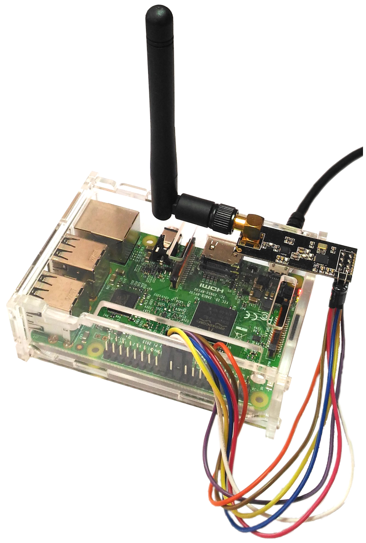

Fig. 5. The WSN central node comprising of Raspberry Pi 3 platform and nRF24L01+ communication module with external antenna.

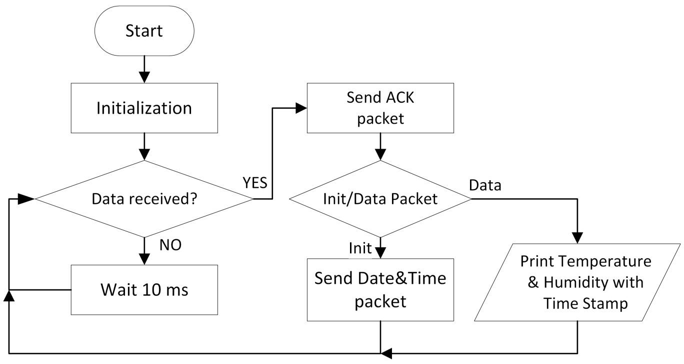

Fig. 6. The flowchart of the developed application using Raspberry Pi 3 platform.

C. Wireless Communication

The wireless communication parameters which could be programmatically set are communication channel, data rate, payload length, cyclic redundancy check (CRC), output power and many more. Specifically, the nRF24L01+ is capable of operation using the carrier frequencies from 2.400 GHz to 2.525 GHz, divided into 126 RF channels. The carrier frequency is set programmatically with step of 1 MHz during wireless module initialization. To prevent an eventual electromagnetic interference with foreign RF networks operating in the same ISM band, it is appropriate to use carrier frequencies above the value of 2.5 GHz. Considering this phenomenon, developed WSN operate at 2.508 GHz. It is obvious that a transmitter and receiver module must operate at the same carrier frequency to communicate with each other properly. The second parameter affecting the communication range is the data rate. In our case, the lowest data rate is more than sufficient for such a simple notification sensor. A long communication range is achieved by setting the data rate to

250 kbps and output power of transmitter to 0 dBm (1 mW). Additionally, the nRF2401+ features the automatic packet handling, the auto-acknowledgment and the auto-retransmission of data packets. However, the CRC is the mandatory error detection mechanism in the packet, and it is either 1 or 2 bytes long.

In our configuration, the two bytes encoded the CRC field. If the CRC fails, then no packet is accepted. If the packet is received and validated by receiver, the acknowledgment (ACK) packet is transmitted back to transmitter. If the ACK packet is not received by transmitter then the auto-retransmission (ART) is activated. The ART is a function that retransmits a packet with defined number of times and period before each retransmission. We set up maximal 15 retransmit trials and 1250 μs delay between trials. All parameters are listed in the Table I. These parameters and features of nRF24L01+ ensure reliable wireless data transmission for long distances (up to 100 m).

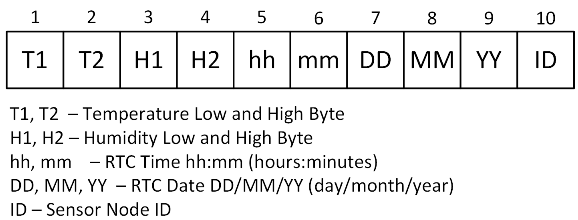

Fig. 7. Structure of the sensor data packet.

The sensor node prepares data packet consisting of 10 bytes with structure described in Fig. 7. The packet length of 10 bytes was taken as it is the smallest packet length that can carry all the necessary sensor information, i.e. temperature, humidity, date, time, and sensor ID. The temperature and humidity data comprise of two bytes, the next 5 bytes are carrying information about time and date. Each individual sensor node has unique ID number which defines location of the sensor node within considered environment (e.g. ID = 0x01 for node with the sensor located in the kitchen). This feature is ensured by the last byte within the sensor packet structure. We defined two types of packets: initialization (INIT) packet and data packet. The INIT packet is sent right after initialization phase of sensor node (see flowchart in Fig. 3). This packet consists of zeros bytes except of last ID byte. The central node detects this packet and sends back current date and time. Then, the sensor node set up RTC date and time according to recursive INIT Packet. Subsequently, the data packets are sent every minute with information about temperature and humidity with corresponding time and date stamp (Fig. 8).

III. Results and Discussion

Performance of the developed WSN system composed of the one WSN central node and two sensor nodes has been tested in a real-life environment - typical three-bedroom flat (2 bedrooms, living room, and kitchen) of 72 square meters (Fig 9). A series of experiments have been conducted to evaluate both, the power efficiency and communication reliability of developed WNS system. Since the WNS central node is permanently driven by power-line, our focus was aimed on the sensor node parameters.

Received:	[156, 105, 0, 37, 14, 43, 22, 2, 19, 1]
Temperature:	25.640935058593747
Humidity:	12.06640625
Time:	14:43
Date (D-M-YY):	22-2-19
Received:	[192, 105, 184, 36, 14, 44, 22, 2, 19, 1]
Temperature:	25.737460937499996
Humidity:	11.9290771484375
Time:	14:44
Date (D-M-YY):	22-2-19

Fig. 8. Sensor node data output in console window on Raspberry Pi 3.

The current consumption has been measured in power-down mode by using the digital multimeter Agilent 34401A. The sensor node drains only 7.39 μA in power-down mode while powering by 3 V coin cell battery. It is slightly higher consumption than calculated consumption (5.76 μA) from datasheet's values of used electronic circuits because of using other necessary electronics components such as pull up resistors which are also consuming a power to some extent. The power consumption of sensor node in active mode (acquiring humidity, temperature, date and time; transmitting data to WSN central node) not overcomes 3.5 mA for period of about 1 second. If we consider the capacity of the used CR1220 battery ($\approx$ 40 mAh), then the estimated sensor node stand-

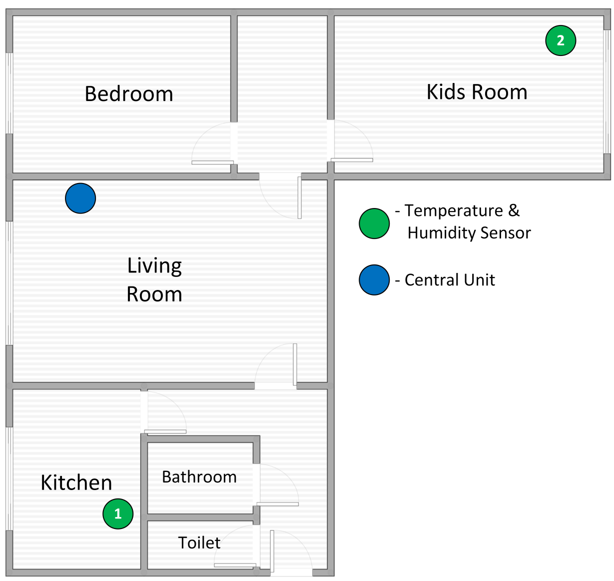

Fig. 9. Disposition layout of the WSNs real-life testing scenario.

by time is about 5412 hours (225 days) excluding battery self-discharge. It should be stated, that this value is strongly affected by waking-up period (e.g. every minute or every 10 minutes). We can compare our solution to very popular IoT solution based on ESP8266 or newer ESP32. ESP product family is a low cost and low-power highly integrated Wi-Fi microchip with full TCP/IP support. The current dissipation of ESP8266EX chip is 20 μA in deep sleep mode (only RTC is working) and 120 mA while sending data using 802.11n standard with transmitter power of 13 dB. The advantage of using ESP microchips is connectivity to existing Wi-Fi network while when using nRF24L01 there is necessary to use another nRF24L01 to transmit and receive data. The disadvantage of ESP is significantly higher power consumption in deep-sleep and active mode comparing to proposed solution. Moreover, connection of ESP to Wi-Fi network takes a few seconds compared to the establishing of connection between two nRF24L01 modules is very quick.

To verify the communication reliability of the developed WNS system, the test scenario was created. For testing purposes, another sensor node with pre-programmed 2 ID was constructed. The sensor nodes and central unit were placed according to Fig. 9. The central unit was placed one meter from the Wi-Fi router and sensor nodes were placed to the longest distance from the central node, including walls and doors alternately closed and opened. At least 10 different Wi-Fi networks (one resident, others from the neighborhood) were detected in the flat. The test was performed during regular inhabitants activities for 48 hours. Every minute, the sensor nodes send data packet (Fig. 7), which means that 2880 data packets were sent during the test from each sensor. The central unit stored received data into the file. The time, sensor ID, temperature and humidity were written as one text line into the file. Following the test, the data file was analyzed. The central unit received two data packets per minute (from ID 1 and 2 sensors), so no data packets were lost, but in 48 cases incorrect data packets were received - 24 times in different periods of time for each sensor. In total, the communication reliability of developed WNS system reached 98.3%. Incorrect received data were not passed CRC thus auto-retransmission function was called. However, 15 retransmit trials seems to be not enough and should be increased in the next design. The next data packet was received correctly after the failure.

IV. Conclusion

In this paper, the design and implementation of low-cost and ultra-low-energy WSN central and sensor node for Smart Home applications is presented. The wireless network is formed by nRF24L01+ transceivers modules. Its price including the environmental sensor does not overcome 11 US dollars in total, thus represents low-cost WNS sensor node solution. Estimated costs of the developed WSN central node is approx. 42 US dollars. Using the cyclic operating state change, the sensor node's power consumption causes that it could be driven by a single coin battery up to 225 days. The performance in terms of WSNs power efficiency and communication reliability has been tested in real-life environment. The proposed designed WSN system meets the requirements outlined, thus providing an affordable and ultra-low-energy solution.

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