Design of Antenna System for Short-Range Wireless Sensor Network

Mirjana Stojilović, Nenad Antonić, and Antonije Đorđević

***Abstract* — One of the ways to send the data collected by a wireless sensor network (WSN) to a remote server application is by using the public mobile-telephone network. This usually implies having a WSN node capable of communicating both with sensor nodes and with the GSM/GPRS/3G network, i.e., the node having two independent RF modules. This paper presents the challenges and solutions of design of an antenna system for this type of WSN node. The major problems are imposed by the high difference of the transmitted power level of one RF module and the maximal allowed input power level of the other RF module. Several solutions for the antennas and the feeding networks are presented and evaluated theoretically and experimentally. The best design was proved to be an RF switching scheme.**

***Keywords* — Antennas, Power dividers, Sensor networks.**

I. Introduction

For the purpose of the FP7-funded project *AgroSense* [1], a WSN was developed by the Institute Mihajlo Pupin (IMP) within the project TR-11022 funded by the Ministry of Science of the Republic of Serbia. Currently, this WSN can support indoor and outdoor monitoring of air temperature, humidity, and light intensity.

One of the final design steps in providing successful and robust communication among WSN nodes was to design adequate antennas and associated feeding networks, i.e., the antenna system. Therefore, further research and development was carried out in collaboration with the University of Belgrade.

This paper presents challenges imposed by the design of antennas for the WSN nodes which require operation of two RF transceiver modules, where one module has a high transmitting power level, and the other is sensitive to high power levels.

The paper is organized as follows. Section II introduces the WSN architecture and Section III presents a sink node, which is the target of our consideration. Section IV describes the antenna system design and also presents the corresponding experimental verification.

II. WSN Architecture

The WSN consists of a number of remote sensor nodes, one sink node, and one server application, as presented in Fig. 1. The nodes are in a star-configuration where all remote nodes communicate only with the sink node. The sink node is the link between the remote nodes and the server application. At the physical layer, the remote nodes and the sink node communicate at the industrial, scientific, and medical (ISM) frequency band centered at 868 MHz, which is used by so-called short range devices (SRD). The communication protocol is a proprietary protocol developed at IMP. On the other hand, the communication between the sink node and the server application is achieved by using the public mobile-phone network at the 900 MHz and/or 1800 MHz frequency bands.

Remote sensor nodes, named MOTE1, are proprietary modules developed at IMP [2]. They provide various on-board sensors to measure the ambient temperature, humidity, and light intensity.

The communication with the server application is provided by the module named GPRS Gateway (GW), which was also developed at IMP. A sink node is composed of one MOTE1 and one GW module. The two modules are stacked, one on top of the other, and exchange data via Serial Peripheral Interface (SPI) communication.

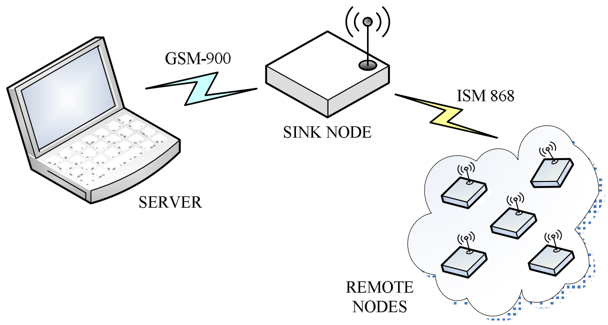

Fig. 1. WSN architecture.

III. Sink Node

Fig. 2 illustrates the interior of a sink node enclosure. The enclosure holds one GPRS gateway module, one MOTE1 module, a rechargeable battery, a 12 V accumulator, and an antenna system. It complies with the IP65 standard, so it can be mounted on trees or poles. The antenna system is composed of an antenna and a ground plane supporting the antenna. This system is in the upper part of the enclosure, assuring that the view in horizontal directions is unobstructed by other electronic and electrical components. The only obstruction may be due to the mechanical support and other outside objects.

Inside the sink node, there are two RF modules. The first RF module is the *SIMCom* SIM5210 [3], a quad-band GSM,

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GPRS, EDGE, and UMTS engine, which can work at the following frequency bands: GSM 850 MHz, EGSM 900 MHz, DCS 1800 MHz, PCS 1900 MHz, and UMTS 2100 MHz. This RF module is active in a short time interval, once or twice per day, when it transmits sensor readings to the server application. During the rest of the day, it is idle. In Serbia, the GSM communication is possible at both the 900 MHz band and the 1800 MHz band. However, rural areas are predominantly covered by the 900 MHz band only. Hence, the uplink (when this module transmits) is in most cases in the frequency range 890-915 MHz. The maximum transmitted power is 33 dBm (2 W) at the 900 MHz band and 30 dBm (1 W) at the 1800 MHz band, with allowed variations ±2 dB. To provide a connection to the antenna, a coaxial cable needs to be attached to the GSC connector that is soldered on the RF module.

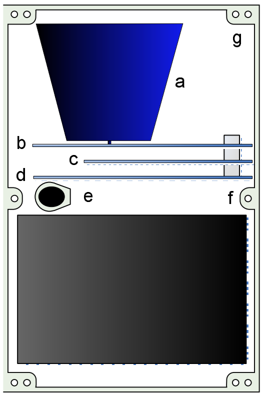

Fig. 2. Sink node. (a) antenna; (b) ground plane; (c) MOTE1 PCB; (d) GW PCB; (e) battery; (f) 12 V accumulator; (g) enclosure.

The second RF module is the *Texas Instruments* sub-1 GHz RF transceiver CC1101 [4], which supports 315/433/868/915 MHz ISM/SRD bands. It is used by the MOTE1 module inside the sink node (as well as by all sensor nodes) to enable communication in the ISM/SRD band centered at 868 MHz. The CC1101 module periodically polls sensor nodes, requesting the measurement results. Depending on the parameters being measured, sensor nodes are polled more or less frequently. Once the answer from the sensor node is received, the node enters the power-down state to save its energy. To provide a connection to the antenna, a coaxial cable needs to be attached to an SMA connector soldered on the MOTE1 PCB. The maximum power transmitted by CC1101 is 10 dBm (10 mW). The receiver saturation level is −14 dBm. However, the maximum allowable input RF power is 10 dBm. Otherwise, the receiver would be damaged. Therefore, the key problem in the design of this antenna system was to increase the receiver immunity to external RF signals generated by the SIM5210 transmitter, in order to prevent catastrophic events in CC1101.

IV. ANTENNA SYSTEM DESIGN

The major requirement for the antenna system was to have good matching at the operating bands (VSWR<2) and to have an omnidirectional radiation pattern in the horizontal plane (with vertically polarized electric field), with a gain of about 0 dBi.

The first step in the antenna design was to choose the antenna type for both RF modules. Since the height of the available space in the enclosure (80 mm) was insufficient to place dipoles, monopole antennas were selected. A relatively large (140 mm by 100 mm), double layer PCB was provided to serve as the ground plane for the monopoles. However, since the dimensions of the ground plane were smaller than half-wavelength at the operating frequencies at the GSM 900 MHz and the ISM 868 MHz band, its influence on the antenna properties had to be considered. Using *Wipl-D* [5], we found that the ground plane substantially affects both the matching and the radiation pattern of the antennas.

The planar inverted-F antennas (PIFAs), normally used in mobile phones, were not considered, because their gain is a few dB lower than the gain of a classical monopole. Sacrificing the output power already at the antenna would decrease the maximal achievable distance to sensor nodes, which was not acceptable.

There exist many off-shelf monopole antennas in the global market. However, importing even the simplest rod antenna, whose price is just a few US$, is complicated and expensive. Among other expenses, there is a requirement to obtain a written permit from the Serbian Communication Agency, which costs more than the whole antenna lot needed for this project. Therefore, we decided to design and manufacture antennas ourselves. We performed antenna computer simulations, followed by experimental verification.

A. Two monopole antennas

In the simulation model, we first mounted two monopole antennas on a common ground plane, as shown in the inset of Fig. 3. The wideband trapezoidal (planar) antenna (labeled 1) is for the SIM5210 module, while the wire antenna (labeled 2) is for the CC1101 module. This solution is simple, as the coaxial cables would just have to be plugged to the antennas. However, it is unacceptable. Namely, as can be concluded from Fig. 3, the coupling between the two antennas near 900 MHz is strong: the transmission (scattering) parameter between the two antenna ports (s_{21}) is about −12 dB. Hence, when the SIM5210 module is transmitting at its maximal power level (35 dBm), the power level at the CC1101 antenna port would be 13 dB higher than allowed, and the C1101 module would likely be damaged.

To avoid the damage, an isolation of at least 25 dB at the 900 MHz band and 22 dB at the 1800 MHz band must be provided. Placing a filter at the CC1101 antenna port may seem to be a good solution. However, it is not. The transition band between 868 MHz and 890 MHz is very narrow (only about 2.5%). Hence, the filter would have to be very steep to provide a reasonable attenuation at 890 MHz. Besides, the filter would have to be carefully tuned, considering the influence of the temperature and the component ageing. Finally, the inherent losses in the filter elements would introduce an intolerable power loss at 868 MHz. Using *Microwave Office* (*MWO*) [6], we calculated the insertion loss of a third-order lumped-element band pass filter, with a quality factor of coils and capacitors of $Q = 200$. It proved to be as high as 10 dB.

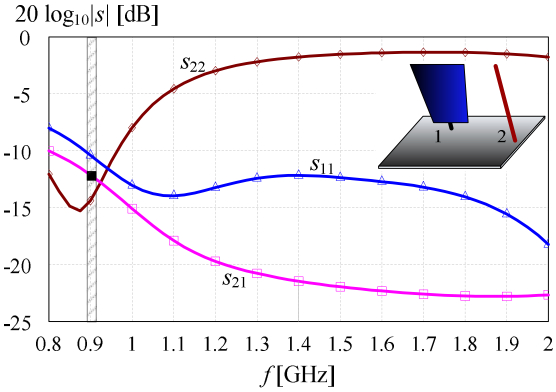

Fig. 3. Scattering parameters of two monopole antennas mounted on common ground plane. The antennas are shown in the inset.

One more reason against using two antennas is that the presence of one antenna significantly affects the radiation pattern of the other antenna. Instead of having the required omnidirectional radiation pattern in the horizontal plane, the pattern becomes distorted with dips of up to 8 dB below the main lobe. Hence, we have decided to use just one monopole antenna.

B. One monopole antenna

In order to cover the whole frequency range from 868 MHz to 1880 MHz, and even allow for future upgrades to 2200 MHz, we have optimized the dimensions of the trapezoidal planar antenna (Fig. 4a). The best omnidirectional radiation pattern is achieved when the antenna is in the middle of the ground plane. However, due to the resonances of this plane, the matching at lower frequencies is not as good as required (VSWR>2 at lower frequencies). Moving the antenna toward edges of the ground plane significantly improves matching, but introduces some irregularities in the radiation pattern. As a matter of compromise, we have selected the antenna position as shown in the inset of Fig. 4b.

The antenna reflection coefficient (s_{11}) as a function of frequency is shown in Fig. 4b. In the frequency ranges 860-960 MHz and 1700-1900 MHz, the standing-wave ratio at the antenna port is VSWR<1.5. The gain in the horizontal plane is about 0 dBi with variations ±1 dB in the lower frequency range, and ±2 dB in the upper range.

At this point, we needed to solve the problem of coupling the two RF modules to the same antenna. A diplexer filter was not considered due to the required narrow transition band, as explained earlier. Hence, two other solutions were considered: a power divider and an RF switch.

Fig. 5a shows the *MWO* scheme of the designed broadband multistage Wilkinson power divider, printed on an FR-4 substrate. The divider provides isolation ($-20\log_{10}|s_{32}|$) between the two RF ports of more than 30 dB in the 860-960 MHz range, and about 24 dB in the 1700-1900 MHz range. It introduces an insertion loss ($-20\log_{10}|s_{21}|$) of about 3.3 dB, which is the expected price to pay when these dividers are used. The divider (with additional filtering at the CC1101 port) enables the RF ports to simultaneously use the antenna, except when the SIM5210 module is transmitting at 900 GHz. In that case, the cross-talk to the CC1101 port will bring the receiver into saturation and, hence, make it deaf (due to the saturation of the receiver).

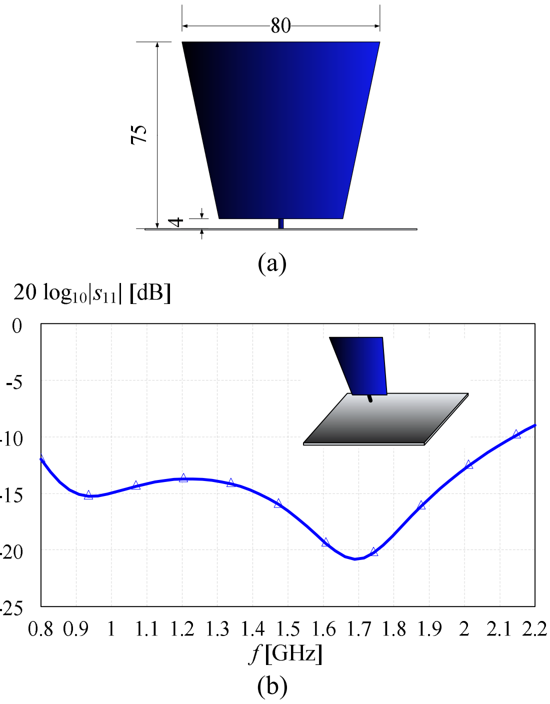

Fig. 4. Optimal trapezoidal antenna: (a) dimensions (in millimeters) and (b) VSWR versus frequency.

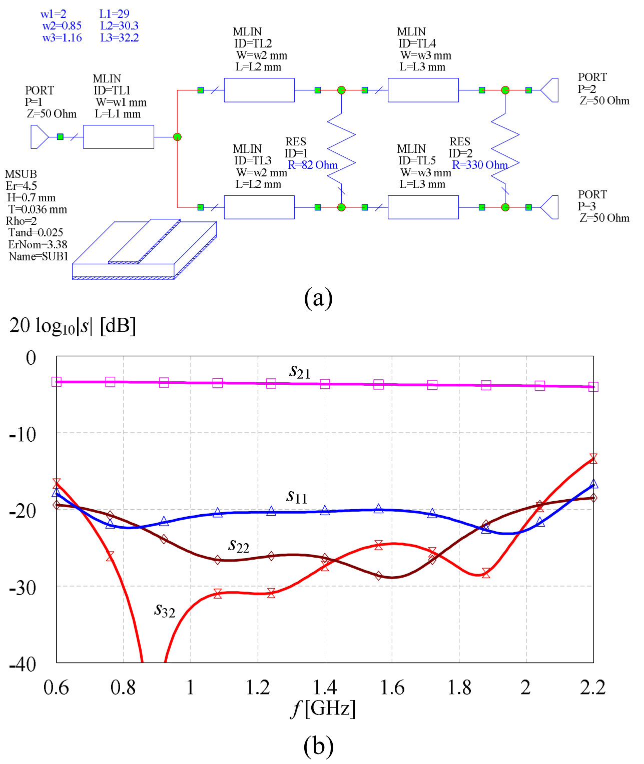

Fig. 5. Broadband Wilkinson power divider: (a) scheme and (b) scattering parameters.

In order to provide a sufficiently good isolation between the two RF modules, the antenna must be almost perfectly matched to 50 Ω, especially near 900 MHz. If the matching is not perfect, the RF power transmitted by the SIM5210 module would be partly reflected from the antenna and then fed to the CC1101 port. For example, if the reflection coefficient of the antenna is –20 dB, assuming the isolation of the Wilkinson divider to be perfect, the effective coupling between the two RF ports will be –26.6 dB. This is just slightly better than the required –25 dB. However, the results in Fig. 4b show the reflection coefficient of only –15 dB, meaning that the antenna and/or the divider must be improved.

To verify the simulations, the Wilkinson divider and the trapezoidal antenna were manufactured. Fig. 6 shows the measured transmission between ports 2 and 3 of the divider when the antenna is soldered to the antenna port (port 1). Curve (1) shows that the isolation between the two ports is insufficient: it is only 18 dB in the critical frequency range 890-915 MHz, as predicted. The isolation can be improved by tuning the antenna or by tuning the divider (by modifying the resistances and by adding a small coupling capacitance), as shown by curves (2) and (3) in Fig. 6. This figure also shows the result of the *MWO* simulations for the divider with the *Wipl-D* result for the tuned antenna (4), taking into account the actual dimensions of the manufactured divider. Hence, curves (2) and (4) are to be compared. The greatest discrepancy between the simulation model in Fig. 5a and the experimental model was in the substrate thickness (0.7 mm, viz. 0.8 mm).

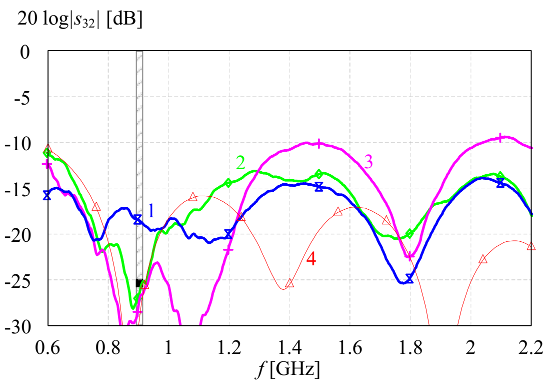

Fig. 6. Measured transmission between SIM5210 and CC1101 ports of Wilkinson divider with trapezoidal antenna: without tuning (1), with tuned antenna (2), and with tuned divider (3), along with simulation results (4).

The resulting design can be used for the present purpose, in particular the version with the tuned divider. However, it has two deficiencies. The first one is the insertion loss of the Wilkinson divider (3.3 dB). The second deficiency is that the isolation highly depends on the antenna matching. If this matching is deteriorated, the safety of the CC1101 receiver is jeopardized. For example, in the presence of snow or ice buildup on the sink node enclosure, the antenna characteristics would drift and the matching would worsen.

The final solution was designed by using high-quality single-pole double-throw *Skyworks* AS193-73 FET switches, as schematically shown in Fig. 7a. In order to improve the isolation toward the CC1101 module when the SIM5210 module is transmitting, a switch was introduced to short-circuit the CC1101 port to ground. The capacitance C was designed so to form a resonant circuit at 1300 MHz with parasitic inductances of the switch and the printed traces. Fig. 7b shows the measured scattering parameters looking into the SIM5210 and CC1101 ports, with the antenna mounted in its place. Excellent performance can be observed. When the SIM5210 module is transmitting in the 900 MHz band, the CC1101 port is isolated by 30 dB. When SIM5210 is transmitting in the 1800 MHz band, the isolation is 27 dB. The reflection coefficient looking into the SIM5210 port is below –15 dB in the whole 900 MHz band, and it is below –12 dB in the 1800 MHz band. When the CC1101 module is connected to the antenna, the reflection coefficient is below –17 dB in the 868 MHz band, and the isolation is about 24 dB. In all cases, the isolation is practically independent of the reflection coefficient of the antenna.

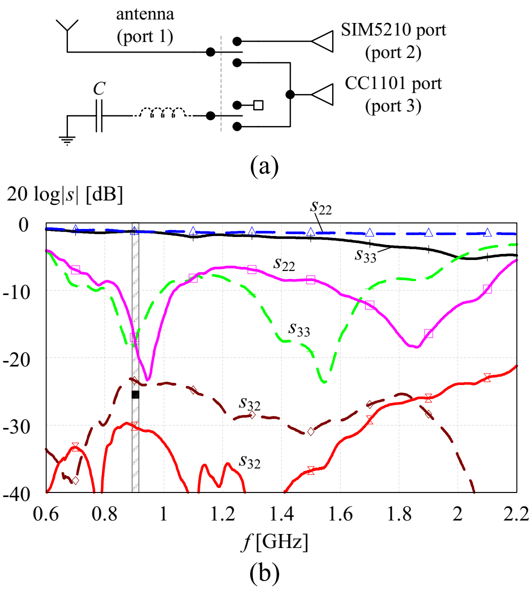

Fig. 7. Antenna with switching network: (a) scheme and (b) measured scattering parameters when the antenna is switched to SIM5120 port (solid) and to CC1101 port (dashed).

The only deficiency of the final solution is that the two RF modules cannot gain a simultaneous access to the antenna, not even in the receiving mode. The sink node must take care to operate the switches properly and interconnect the antenna to the appropriate module with appropriate timing. However, this is not an issue, because the present communication protocol does not require simultaneous operation of the two RF modules.

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