Reconfigurable Sensing Antenna: A Slotted Patch Design With Temperature Sensation

Fan Yang, Senior Member, IEEE, Qian Qiao, Juha Virtanen, Student Member, IEEE, Atef. Z. Elsherbeni, Fellow, IEEE, Leena Ukkonen, Member, IEEE, and Lauri Sydänheimo, Member, IEEE

Abstract—A reconfigurable sensing antenna (RSA) concept is presented in this letter, where a physical sensor is integrated into a reconfigurable antenna as the control unit. The basic structure and operation principle of the RSA are described in details. To illustrate this RSA concept, a slotted patch antenna with temperature sensation is designed, fabricated, and tested. In this design, distilled water is integrated into the antenna substrate as the sensing material because its permittivity changes with temperature. Thus, the antenna frequency is reconfigured according to the environmental temperature. The measurement results demonstrate an effective sensing range from 17°C to 70°C. Due to the passive and low-cost features, the proposed RSA has a promising potential in wireless sensing network applications.

Index Terms—Patch antenna, reconfigurable antennas, reconfigurable sensing antennas (RSAs), wireless sensor.

I. INTRODUCTION

In conventional antenna designs, radiation characteristics, such as operation frequency, input impedance, and radiation patterns, are fixed once they are designed and fabricated. In recent years, reconfigurable antennas have attracted increasing attention because the radiation characteristics can be flexibly changed using control electronics such as p-i-n diodes, varactors, and microelectromechanical (MEM) switches [1]–[4]. This letter proposes a reconfigurable sensing antenna (RSA) design, where a physical sensor is used as the control unit instead of conventional active electronics. In this design, the function of the antenna is not only to transmit and receive electromagnetic waves, but also to sense the variation of surrounding environments.

Wireless sensor networks have a wide range of applications in military, industry, and civil areas [5]. In order to deploy a large-scale wireless sensor network economically, each sensor node should have a low cost. Furthermore, although passive nodes have limited communication ranges, they are preferred in various applications since it can maintain long time effectiveness without the need of battery change. Reconfigurable sensing antennas provide a promising solution to satisfy the above low-cost and passive requirements. Recently, several antennas have been designed to monitor the humidity level [6], [7], gas concentration [8], movement [9], and temperature [10].

This letter introduces a generalized RSA concept and presents the RSA structure and operation principle in details. Next, a slotted patch antenna that can sense surrounding temperature is designed to illustrate the RSA operation. The sensing material, antenna geometry, radiation characteristics, and temperature sensation are presented. Finally, experiments are conducted to validate the performance of the proposed RSA.

II. RECONFIGURABLE SENSOR ANTENNA CONCEPT

A. RSA Components

An RSA consists of a sensor, an antenna, and an integrated chip (IC), as illustrated in Fig. 1. The sensor transforms the environment information into a certain electric parameter. Under the control of this parameter, the antenna receives and scatters electromagnetic waves in the space. An IC is connected to the antenna terminal, which contains the antenna information such as an identification number.

The physical sensor in an RSA can be either a lumped circuit element, as shown in Fig. 1, or a distributed bulky material. Through the sensor, environmental information such as humidity, pressure, or temperature will be converted into certain electric parameters, including resistance, capacitance, inductance, material permittivity, etc. Passive sensors are preferred in RSAs because no battery is needed in the operation.

Various antennas can be used in RSA designs. A dipole-type antenna is shown in Fig. 1; microstrip patch antenna, slot antenna, and other configurations can also be designed. A critical issue in the antenna design is how to effectively integrate the sensor into the antenna as the control unit. A lumped sensor can be connected at the antenna terminal to change its input.
impedance, as shown in Fig. 1, while a distributed sensing material can also be used as antenna substrate to affect the resonant frequency.

An IC is used here to complete the RSA as an independent functional unit. Hence, there is no need to connect the antenna to an additional RF module for operation. The IC in each RSA has unique information, which helps to distinguish it from others in practical application environments where many RSAs are deployed. Passive IC is suggested in RSA designs, and the antenna receives power from an incident electromagnetic wave to activate and support the IC operation.

B. Operation Principle

Since the proposed RSA is a passive standalone device, it operates in a backscattering mode. An electromagnetic wave is radiated from a center station and carries certain request commands. The RSA receives both energy and commands from this incident wave. The IC works with the received energy and responses to the request commands. The response is then encoded into a backscattering wave, which is to be received by the center station.

Although the above procedure is similar to the operation of an RFID tag, a significant difference exists between an RFID tag and an RSA device. An RFID tag uses a conventional antenna that has fixed radar cross section (RCS), whereas the RSA device uses a reconfigurable antenna whose RCS signature is changed by a sensor. When an RSA operates, the variation of environmental condition stimulates the sensor and results in a change in the sensor’s corresponding electrical parameter. It then reconfigures the RCS of the antenna, such as the signal strength level and the resonant frequency. Therefore, the backscattered electromagnetic (EM) wave from the RSA contains not only the IC information, but also the sensor information.

The proposed RSA is also different from conventional RFID sensors in how the sensor is integrated. In many RFID sensors designs [11], [12], the sensors are directly designed and integrated into IC chips, while in RSA devices, the sensors are integrated with antennas. As a consequence, the sensors are not limited by the fabrication considerations of the semiconductor ICs, such as the material selection and size constrain. In addition, when a new type of environmental information needs to be monitored, only the antenna needs to be redesigned, which has a lower cost and shorter turnout time than a new IC design.

III. SLOTTED PATCH DESIGN WITH TEMPERATURE SENSATION

In this section, a slotted patch antenna is designed to demonstrate the RSA concept. Distilled water is used as a distributed temperature sensor, and a commercial Higgs-2 UHF chip [13] is used as the IC attached to the RSA.

A. Antenna Geometry

The antenna geometry is shown in Fig. 2, which consists of three layers: two FR4 layers to support the metal ground and patch, and a middle Duroid/5880 layer with a center square cavity to contain water. A patch antenna is selected in this design because of low cost and easy fabrication. Furthermore, the narrow antenna bandwidth, which is usually disadvantageous in many communication systems, is actually an advantage in the RSA design because it increases the frequency sensitivity to the environment. In addition, the ground plane helps to minimize the effect of the platform where the antenna is installed. Thus, this design can also work on metallic objects [14]. In addition to a conventional probe feed that needs to drill a hole in the substrate or a microstrip line feed that needs an extra feed line, a slot feed is adopted in the proposed design and a Higgs-2 IC chip is easily mounted in the middle of the slot.

Since the water permittivity is a function of temperature, it is chosen as a low-cost sensing material in this design. The measured complex permittivity is shown in Fig. 3, which decreases with the temperature [10]. The dielectric constant is about 88 at 0°C and becomes 67 at 60°C. Therefore, it can be used to effectively reconfigure the resonant frequency of the patch antenna.

B. Simulation Results

The antenna dimensions are designed with Ansoft HFSS [15] and an in-house finite-difference time-domain (FDTD) program. The thicknesses of the FR4 and Duroid/5880 substrates are 1.6 and 3.2 mm, respectively. The overall ground plane size is 100 × 100 mm², and the patch size is 38 × 38 mm². The size of the water pocket is 40 × 40 mm². The slot length is 12 mm, and slot width is 11.5 mm.

The simulated reflection coefficient of the antenna is shown in Fig. 4. As the temperature increases, the dielectric constant
Fig. 4. Simulated $S_{11}$ of the RSA under various temperatures.

Fig. 5. Simulated RG of the RSA under various temperatures.

Fig. 6. Three layers of the proposed RSA.

IV. EXPERIMENTAL RESULTS

An antenna prototype is fabricated and tested. Fig. 6 shows the three layers of the proposed RSA. In the figure, from left to right are the Duriod/5880 with cavity for water, top FR4 substrate with an IC attached to the slotted patch, and bottom FR4 with ground. Fig. 7 is a photograph of the final RSA prototype. The measurement of the RSA is conducted in an anechoic chamber, as shown in Fig. 8. The RSA is placed inside an empty plastic container and is attached to its back wall. The reason for doing this is to limit the airflow and control the temperature around the RSA. The ambient temperature is held stable by using a heater and an air cooler simultaneously. The measurements were performed with a Tagformance device [16] that can read both the IC information and the transmit/receive power levels.

The minimum transmitted power ($P_{TS}$) that can activate the RSA is measured. The relation between the minimum transmitted power and the threshold IC received power ($P_{IC}$) is as follows:

$$P_{IC} = L_{fwd}P_{TS}G_{RSA}.$$  \hspace{1cm} (1)

The equivalent isotropic radiated power is 3.28 W. Fig. 9 compares the read ranges between simulation and measurement. Simulated results are obtained by substituting $P_{IC}$ (−14 dBm) and simulated realized gain ($G_{RSA}$) into (2), while the measured results are obtained by substituting the measured $P_{TS}$ and $L_{fwd}$ into (2). The read range varies with frequency, and the frequency where the maximum read range is achieved is extracted as the tag’s resonant frequency. The frequency resolution could be improved by increasing the $Q$-value of the patch antenna. As the temperature increases, both the antenna frequency and read range increase. It is worthwhile to point out that the frequency
is higher than those in Fig. 5 because the water layer in the RSA prototype is slightly thinner than the designed value.

Fig. 10 is the sensitivity curve of the temperature sensor. A second-order polynomial function is used to describe the dependency between the temperature and resonant frequency

\[ f(\text{MHz}) = C_2 T^2 + C_1 T + C_0. \]  
(3)

Here, \( T \) is the ambient temperature in Celsius degrees, and the coefficients \( \{C_2, C_1, C_0\} = \{-0.0021, 0.5181, 918.8145\} \). The average error between the measurement and empirical (3) is 0.075 MHz.

V. CONCLUSION

This letter presents a general RSA concept, which consists of a physical sensor, an antenna, and an integrated chip. The operation principle of the RSA is described in details, and a slotted patch antenna is designed as an example. When distilled water is used as a sensing material, the resonant frequency of the antenna can be reconfigured by the environmental temperature. Operating at the UHF band (900 MHz), the RSA prototype demonstrates a temperature sensing range from 17°C to 70°C, which is the effective scope of the measurement facility. In practice, the water can work from 0°C to 100°C as the sensing material. To further increase the temperature sensing range, other liquids such as coal oil may be considered. Since the proposed RSA is a low-cost and passive device, it could enable an economic deployment of large-scale wireless sensor networks.

REFERENCES