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A dual-band antenna for extending cellular coverage by using energy harvesting strategy

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The widespread use of sensor nodes forces a straightforward, low-cost and easy-to-implement design of these nodes. Instead of using separate batteries and antennas, this letter proposes a dual-band microstrip antenna for both communication and energy harvesting applications. The energy required for the sensor node is harvested from the broadcast television band and then used in the cellular phone communication band. A previous design of a circular polarised broadband patch antenna is adapted and optimised for the defined requirements with the electromagnetic simulation software CST Studio Suite. The simulations helped in an antenna design with a reflection coefficient below -10 dB in the 600 MHz – 700 MHz television frequency band for the energy harvesting. Furthermore, the antenna is also able to operate in the 850 MHz cellular mobile phone communication band, in order to provide coverage in shadowed remote areas or even to be of use for the transmission of the sensor data. The final design is prototyped and then characterised through the measurement of the reflection coefficient.

Introduction: During the past several decades, antennas have become an essential part of people's daily lives. These antennas found their use in many applications, such as radios, televisions, smartphones, laptops, notebooks and all kinds of sensors. Throughout the years however, there has been an increasing demand for cheap, compact and reliable integrated antennas, as microstrip patch antennas. Mobile and hence wireless communication systems, like sensor networks, also need batteries, where both the quality and the lifespan of the battery itself and the energy-saving use in the communication link are important aspects.

Instead of using batteries, the antenna included in the wireless device could harvest the required energy in one communication band and establish links in another frequency band. Because of the common design criteria in wireless sensor networks, mostly low-profile, lightweight and low-cost antennas such as microstrip antennas are extensively used. They are relatively inexpensive to design and manufacture because of their simple two-dimensional physical geometry, and consist of a patch of high conductivity metallisation in copper on a grounded substrate in the same material, a fraction of the wavelength separated by a dielectric substrate. These antennas can be used in both low-power transmitters and receivers. A patch antenna is the most common type of microstrip antenna and is usually narrowband, wide-beam and low-gain. However, their performance has matured considerably during the past 25 years, overcoming many of their limitations [1]. Patch antennas using energy harvesting and communication in the same frequency band have already been described in the literature [2], [3].

The *a priori* assumptions are that TV radio coverage extends largely along European countries, TV broadcasting manages important transmitted powers, and RF to DC conversion efficiency can range from 10 to 70% [4]. Thus, the TV frequency band would provide energy enough to support a wireless system with low traffic requirements (cellular communications in remote areas or sensor networks). In that situation, a standard base station with its own wired energy supply could be unaffordable or non-profitable for service providers. Thus, self-sustaining approach would emerge as a way to solve that communication problem in faraway places. With this focus, we describe in this letter a dual-band microstrip antenna design, serving a twofold purpose: energy harvesting in the 600 MHz – 700 MHz television frequency band and wireless communication in the adjacent 850 MHz frequency band.

Design and simulations: A microstrip patch antenna is characterised by a small bandwidth and a low radiation efficiency, because the cavity formed by the antenna patch and the ground plane itself has a very high Q-factor and low radiation efficiency [1]. This main disadvantage can be solved by increasing the thickness of the substrate and choosing a lower permittivity one, both resulting in larger antenna dimensions for a given resonance frequency. However, a more convenient method is changing the shape of the patches and, more specifically, including more edges, compared to a rectangular shape, leading to additional apertures from

which the structure can radiate. The corresponding fields tend to concentrate at the edges of the patch, thus high-field concentrations at the edges lead to higher losses and can therefore lower the radiation efficiency. A good trade-off should be reached.

The basis for the proposed design is a previous patch antenna prototype made for both energy harvesting and communication in the 2.5 GHz frequency band [2]. The design consists of two pairs of half-wavelength dipoles, a centre patch, a stub located at the bottom of the centre patch and four connector patches. A microstrip edge feeding technique is selected, as being the most convenient and a probe feed is connected to the stub for the port.

The newly proposed design, however, is realised by going through a sequence of different steps. The substrate is made of FR-4 (Flame Retardant 4) with a dielectric constant $\epsilon_r = 4.3$ and a loss tangent of 0.025. For the metallic top layer, copper was used with a thickness of 0.035 mm. First off, the length of the dipoles was rescaled (considering the design frequencies and the dielectric constant of the FR4 substrate) to support the 600 MHz – 700 MHz energy harvesting frequency band, resulting in dipoles with a length of approximately 12 cm. To achieve impedance matching, the widths of all patches except the connector itself were scaled using the same factor as above. Because all dimensions have increased compared to original design, the substrate size had also been increased to 280 mm by 280 mm. There is almost no influence on the antenna characteristics.

As a second step, the corners of the connectors were chamfered for smoother transition, which improves the reflection coefficient response. In a third step, all the antenna dimensions were optimised with the electromagnetic simulation programme CST Studio Suite, resulting in lengths of 112.33 mm and 115.89 mm for the dipole antennas. Impedance matching and, therefore, good reflection coefficient for both the 600 MHz – 700 MHz and the 850 MHz frequency bands are achieved.

Once optimised, as a final step, the determination of the best substrate thickness is determined. Apparently, a thickness of 2.4 mm is obtained. For practical reasons, however, a thickness of 1.6 mm was used, barely influencing the above mentioned optimal solution. Fig. 1 gives the final design.

The resulting simulated reflection coefficient is depicted in red dashed line in Fig. 2, labelled as 'simulated'. Values of respectively -35.2 dB at 632 MHz and -32.1 dB at 850 MHz were achieved. The bandwidth of the energy harvesting band with $|S_{11}|$ below -10 dB is 15 MHz, and that of the communication band 19 MHz. The bandwidth of the energy harvesting band could be enlarged in following steps, so it can be concluded that all design criteria are met.

The far field radiation patterns at both 632 MHz and 850 MHz resonance frequencies are given in Fig. 3 and Fig. 4 respectively. The gain at the 632 MHz resonance frequency is 7.1 dBi and the beamwidth is 82.2°. For the 850 MHz resonance frequency, the gain is 4 dBi with a beamwidth of 106.2°. In this case it is worth noting that the radiation pattern symmetrical in the main lobe and rather skewed in the back one.

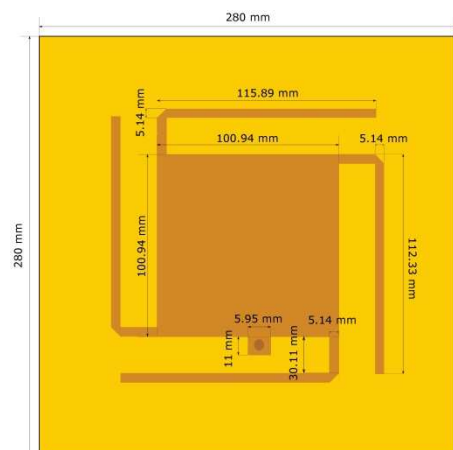


Fig. 1 Antenna layout of final design.

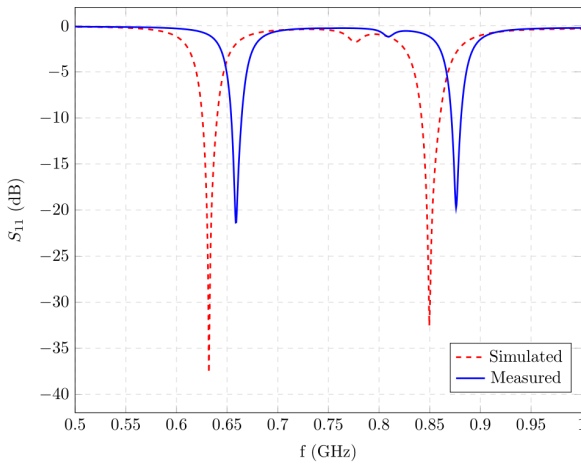


Fig. 2 Simulated and measured S_{11} parameter.

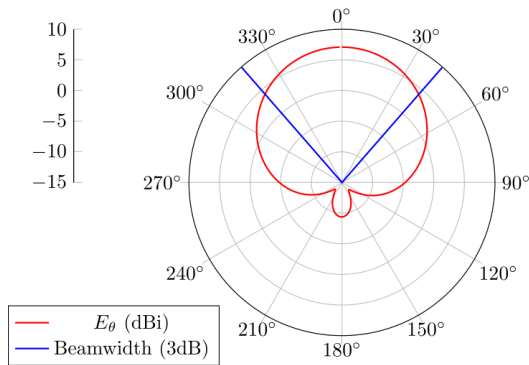


Fig. 3 Simulated radiation pattern of final design at resonance frequency of 632 MHz and $\varphi = 0^\circ$ (energy harvesting in the proposal).

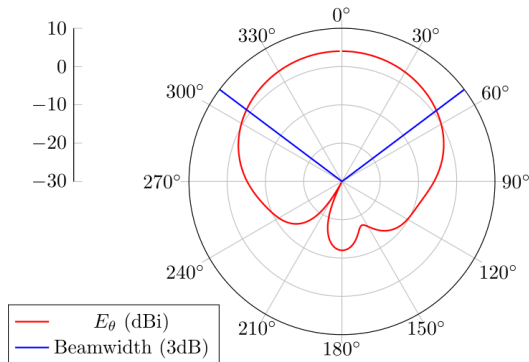


Fig. 4 Simulated radiation pattern of final design at resonance frequency of 850 MHz and $\varphi = 0^\circ$ (wireless communication in the proposal).

Fabrication and measurements: The fabricated antenna is shown in Fig. 5. With the prototyping of this practical design, measurement of the reflection coefficient can be performed. The equipment used was the N5222A PNA Microwave Network Analyser from Agilent Technologies and a 85052D 3.5 mm calibration kit.

The measured reflection coefficient is depicted in blue full line in Fig. 2, by the trace labelled 'measured'. As it can be seen, there is a reasonably good approximation between the simulated and the measured results. The resonance frequencies have however slightly shifted to respectively 658 MHz and 876 MHz, but they still fall within the bands of interest. These frequency shifts are consequences of the prototyping accuracy (including the substrate thickness) and the connector welding, which could indeed induce a certain mismatch. Furthermore, the true bandwidth of the energy harvesting band (10 MHz) is smaller in size than the simulated ones (more than 15 MHz).

The bandwidth can be increased substantially by using an aperture coupled feed, although the production cost increases drastically because of the multi-layered substrates. The reflection coefficients are approximately -20 dB at these resonance frequencies.

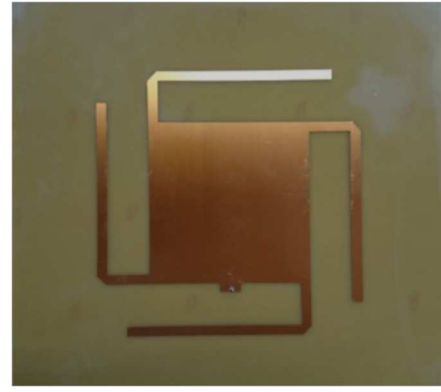


Fig. 5 Prototyped antenna.

Conclusion: In this letter, a new and convenient antenna design for energy harvesting and communication applications has been proposed. The energy harvesting band is the 600 MHz – 700 MHz frequency band, whereas the communication band is 850 MHz. It was shown that the prototype on which the design is based could be rescaled, redesigned and improved in such a way that it achieved the required design criteria. A prototype has been built and tested, supporting the validity of the design. Although the size of the antenna is not valid for mobile terminals, its applicability in small base stations to increase coverage in remote places or to support links for sensor networks gives it a chance of success.

The implementation environment relates to faraway areas with low population and, so that, null interest of service providers in deploying standard base stations to provide wireless communication coverage. However, such remote places are used to get radio broadcasting television signals, which could be used to harvest energy that supplies the wireless part of the system. Energy harvesting experts reported efficiencies in RF to DC conversion from 10 to 70%, which would be enough to support low rate demanding links.

A possible improvement would be the use of the presented design as the unit cell of a matrix array. After some adjustments to take into account possible mutual coupling effects, the array could be tuned to both frequency bands of interest.

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