Co-Design of Dual-Purpose Heatsink Antenna for Multi-Source Ambient Energy Harvesting

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***Abstract*— IoT infrastructure involves billions of devices that must be self-sustainable. Using ambient energy sources to power IoT devices is a promising solution. Ambient RF and thermal energy (diurnal temperature fluctuations) harvesters have great potential since both are available continuously. Smart integration is required for these two harvesters to create synergy and collect more energy. Here, a dual-purpose triple-band heatsink antenna for multi-source ambient energy harvesting is presented. Heatsink antenna serves as a receiving antenna for the RF energy harvester and serves as a heatsink for the thermal energy harvester (TEH). Co-optimization of the heatsink antenna is performed in Ansys HFSS and Ansys Fluent simultaneously. Heatsink antenna operates at GSM900, GSM1800, 3G bands with measured gains of 3.8dB, 4dB, 5.3dB respectively. Antenna gain is doubled (~3dB) and the TEH performance is tripled (200%) when the heatsink fins are integrated, emphasizing the benefit of the co-design and smart integration via heatsink antenna.**

***Index Terms*—heatsink antenna, ambient energy harvester, RF energy harvester, thermal energy harvester, self-powered IoT devices.**

I. INTRODUCTION

Internet of Things (IoT) is a network of physical objects embedded with smart devices that can collect, process, and exchange information with each other via the Internet. The number of these devices is increasing extremely fast and is expected to reach 75 billion in 2025. [1]. A huge number of IoT devices is accompanied by the problem of power consumption which is considered as one of the main bottlenecks of IoT implementation. This problem could potentially be solved by collecting the ambient energy to power the IoT devices. There are several types of ambient energy harvesters available, such as mechanical, thermal, solar, and electromagnetic [2] that can be used either to extend the battery life or get rid of the battery completely. However, using single stand-alone ambient energy harvesters in a real-world application is a fragile strategy since ambient energy sources tend to be unpredictable. Therefore, integrating two or more ambient energy harvesters into one module could solve the problem by enabling a more robust operation. In [3] we demonstrated that the ambient RF energy harvester (from GSM and 3G) and transient thermal energy harvester (from temperature fluctuations of the day and night cycle) are good candidates to be combined into one module since both work 24 hours a day consistently, unlike other sources. However, smart integration is required to 1) reduce the size of the combined unit and use the space efficiently by sharing common components, and 2) not deteriorate the performance of each other, and instead, boost the amount of collected energy by achieving synergy between the two harvesters. Using a heatsink antenna is a potential option where it can be used as a receiving antenna, part of the RF energy harvester (rectenna), and as a heatsink that can enhance the performance of the thermal energy harvester (TEH). However, the design of such a dual-purpose component requires careful co-optimization from the electromagnetic (EM) radiation perspective as well as the heat transfer perspective to make the most of the heatsink antenna performance.

There are many applications where antennas operate in hot or temperature-varying environments, however, not many works utilize the concept of dual-purpose antennas. There are only a handful of heatsink antenna papers published in the literature [4-8], however, there are considerable distinctions compared to this work. First of all, heatsink antennas have never been used in ambient RF energy harvesting application, since many existing works are limited to the heat dissipation from ICs. Secondly, in published works, simple single-band microstrip patch antennas are designed with some commercial or non-optimized heatsinks attached to the patch antennas. Thirdly and most importantly, co-optimization between the antenna performance and the heat transfer performance is not performed. Since the heatsink antenna is a dual-purpose component, trade-off analysis is required by understanding the fundamentals of the heat transfer theory along with the antenna design theory. Thus, complete design trade-offs and design guidelines are unavailable for heatsink antenna design.

This paper presents a triple-band dual-purpose heatsink antenna for the first time, which has been co-optimized from the antenna EM radiation perspective as well as the heat transfer perspective simultaneously. Co-design of the heatsink antenna helps smartly integrate the RF energy harvester and the TEH into one module by boosting the performances of both harvesters considerably. Heatsink antenna, in the shape of fractals, has been designed on the complex body of the TEH. The antenna operates at 900 MHz, 1800 MHz, and 2100 MHz frequencies with measured gains of 3.8 dB, 4 dB, and 5.3 dB respectively. Ansys high-frequency structure simulator (HFSS) has been used to design the heatsink antenna from the EM radiation perspective, whereas computational fluid dynamic (CFD) simulator Ansys Fluent has been used to design the heatsink fins from the heat transfer perspective. Heatsink antenna gain increased by ~3 dB for all three frequencies compared to the flat antenna without heatsink fins. In turn, energy collected from the TEH has been tripled when the heatsink antenna is assembled on the side faces of the TEH box. Performance enhancement of both harvesters highlights the utility of the smart integration through heatsink antenna

II. Heatsink Antenna Design

The heatsink antenna in this work is designed for the multi-source ambient energy harvester which consists of an RF energy harvester and the TEH. It is essential to understand the body structure and electrical properties of materials to create the HFSS model of the TEH for heatsink antenna design. Moreover, this step is also challenging due to the interdisciplinary nature of the project, where materials of the TEH's body are unusual for the RF characterization. V antenna is designed for this work, formed by two legs perpendicular to each other, occupying the two adjacent side faces of the TEH box. Since the available ambient RF power is relatively small, the heatsink antenna must be able to collect from several available frequency bands simultaneously, to enhance the collected energy [9]. Thus, a single-band V antenna is modified into a triple-band antenna by using the concept of fractals [10-11]. Fractals are designed by the iterative process of copying self-repetitive scaled-down structures in a deterministic or random manner [12]. Cantor fractal is used for this work due to its rectangular shapes that can be used as a baseplate for fins of the heatsink antenna. Cantor fractal follows the pattern where the first rectangular part is copied and divided into three equal rectangular pieces and the middle one is deleted. Three iterations are required to achieve triple-band performance for the 2D flat antenna on the body of the TEH (Fig. 1(a)). The length of the baseplate is dictated by the frequency of operation. The first iteration rectangular baseplate length is 82 mm which is equivalent to the λ wavelength at 2.1 GHz on ABS plastic dielectric ($\varepsilon_r = 3$, tan $\delta = 0.004$) which is used as a housing for the TEH. 2D flat antenna is transformed into the heatsink antenna as shown in Fig. 1(b) by integrating co-optimized fins, whose dimensions such as fin length, thickness, and spacing are studied in Ansys HFSS and Ansys Fluent simultaneously.

The relationship between the fin heat transfer rate and the length of the fin is the hyperbolic tangent function, *tanh(x),* and it has its maximum when the *L* is infinity. However, in a practical scenario, the value of the function saturates for a certain fin length. Fig. 1 (c) shows that the amount of transferred heat saturates when the length of the fin exceeds 20 mm. Additional fin length adds negligible effect in terms of the heat transfer performance however makes the heatsink more heavy, bulky, and costly. The gain of the heatsink antenna increases with the increase of a fin length. This relationship can be explained by the fact that the large part of the heatsink antenna is in the air (lower loss) and experience less influence from the lossy body of the TEH (radiation efficiency increase), compared to the 2D flat antenna. Thus, as shown in Fig 1(d), when the fin length is 25 mm the antenna radiation efficiency doubles, which is an increase by ~3 dB in terms of gain, for all three frequencies. As no compromise is required from both the antenna radiation performance and the heat transfer performance, a fin length of 25 mm is selected for the project as an optimal value.

Tightly spaced thin fins are preferred for the highest fin effectiveness, however, it is important to mention that fins must not be placed too close to each other where the airflow between the fins is severely impeded [13]. Minimum fin thickness is dictated by the manufacturing machine capability, which is a computer numerical control (CNC) machine in our case. Fin thickness of 2 mm is selected as a practical value. Fin spacing is identified through Ansys Fluent simulation where the natural convection airflow is imitated with the convection coefficient of 10 $W/m^2 \cdot K$ [14]. The optimal spacing between fins is between 4 mm and 8 mm in a practical scenario of ambient energy harvesting. From the antenna's radiation perspective, the fin thickness and spacing have little to no effect on the antenna performance since most of the stronger currents are located on the baseplate near the feed point. Therefore, heat transfer optimization was prioritized regarding the thickness and spacing of the fins.

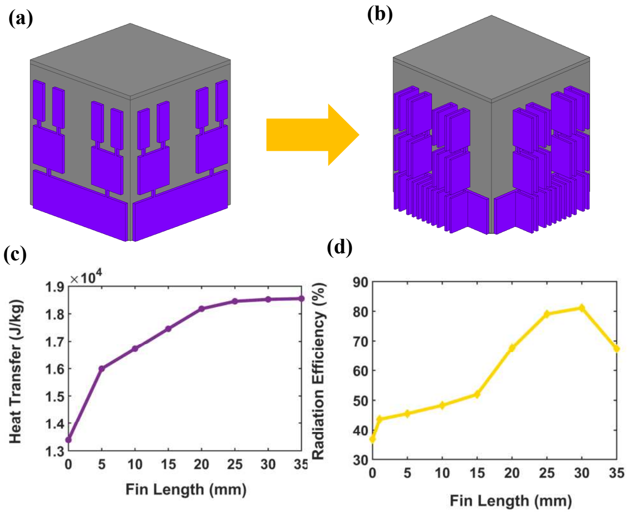

Fig. 1. (a) 2D flat antenna with three Cantor fractal iterations (b) Heatsink antenna (c) Heat transfer rate as a function of fin length (d) Antenna radiation efficiency as a function of fin length

III. Heatsink Antenna Characterization

Heatsink antenna is manufactured through the CNC machine and assembled on the body of the fabricated TEH, as shown in Fig. 2 (a). Fig. 2 (b) shows the measured reflection coefficient (S_{11}) of the heatsink antenna that has a decent match with the simulation results at the required frequency bands 900 MHz, 1800 MHz, and 2100 MHz. In addition, the heatsink antenna has been characterized inside the anechoic chamber for its radiation performance. The heatsink antenna has measured gains of 3.5 dB, 4 dB, and 5.3 dB at 900 MHz, 1800 MHz, and 2100 MHz frequencies respectively as shown in Table I.

IV. Conclusion

In this paper, we presented a dual-purpose triple-band (900 MHz, 1800 MHz, and 2100 MHz) heatsink antenna for smart integration of the RF energy harvester and the thermal energy harvester. The antenna is designed through co-optimization of the EM radiation performance of the antenna using Ansys HFSS and the heat transfer performance of the heatsink fins using Ansys Fluent. An antenna performance improvement is achieved in terms of radiation efficiency (from ~40% to ~80%), resulting in gain improvement by ~3dB compared to the flat version of the antenna (without fins). Moreover, the performance of the thermal energy harvester is tripled (~200%) when the optimized fins are integrated. Performance enhancement of both RF energy harvester and the thermal energy harvester highlights the utility of the smart and monolithic integration of two harvesters through using a co-optimized heatsink antenna.

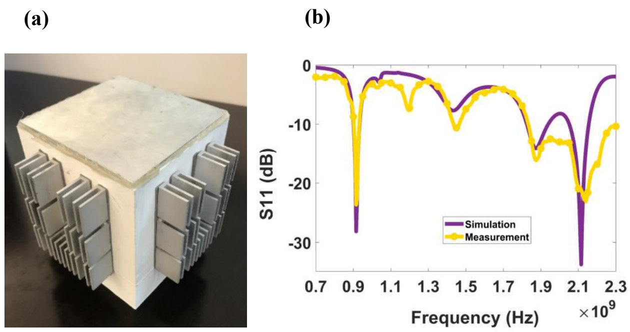

Fig. 2. (a) Fabricated heatsink antenna assembled on the body of the thermal energy harvester (TEH) (b) Reflection coefficient of the heatsink antenna

TABLE I

Gain of the Heatsink Antenna

Frequency	Gain (dB)
900 MHz	3.8
1800 MHz	4
2100 MHz	5.3

Acknowledgment

This work was supported by the KAUST Sensor Initiative, under award OSR-2015-Sensors-2700.

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