Multi-source ambient energy harvester based on RF and thermal energy: Design, testing, and IoT application

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Abstract
Billions of wireless sensing devices must be powered for IoT applications. Collecting energy from the ambient environment to power sensor nodes is a promising solution. Solar energy has been one of the main sources of ambient energy due to its availability, higher power density, and the maturity of the solar photovoltaic industry. However, there are many scenarios (indoor environment, outdoor environment during nighttime, poor weather conditions, underground, etc) where ambient solar energy is either not available or not sufficient for practical applications. For such scenarios, other renewable sources of energy must be sought. Typically, not enough power is collected from one ambient source to charge sensor nodes for continuous operation. In this work, we present a multi-source energy harvester that collects RF and thermal energy (both available 24 hours) from the ambient environment simultaneously. The RF energy harvester is multi-band and collects power from GSM (900, 1800 MHz) and 3G (2100 MHz). The thermal harvester converts diurnal temperature fluctuations to electrical energy using high thermal effusivity phase change material. Extensive field testing has been performed in three different conditions—outdoors, indoors, and buried underground—to highlight the usefulness of the multi-source energy harvester in all these environments. When one source is disabled, the harvester still generates energy from the remaining active source and can enable continuous operation of futuristic IoT sensors. As a proof of concept, a real-world IoT application is demonstrated, where temperature and humidity sensors are powered by the multi-source energy harvester. Continuous robust operation of the sensors and wireless data transmission after each 3.7 seconds are expected when both harvesters operate in full mode. Scenarios, where only single thermal energy harvester or only single RF energy harvester operates, are also demonstrated and data transmission with average time intervals of 30 seconds and 9 minutes is achieved, respectively.

Keywords
ambient energy sources, multi-source energy harvester, RF energy harvesting, self-powered IoT wireless sensors, thermal energy harvesting
INTRODUCTION

It is estimated that the number of wireless devices will reach 75 billion in 2025. This is possible because of the emerging Internet of things (IoT) paradigm, which will connect a huge number of devices and sensors into one network to optimize and facilitate people's daily activities. It is clear that the power consumption of these devices is the main limitation with regard to large-scale implementation of the IoT network. Ideally, the sensor nodes must be autonomous, self-powered, and low-cost. Collecting energy from the ambient environment and using it to power IoT sensor nodes might solve the issue of power consumption. In general, IoT devices can benefit from solar energy, as light is available in most outdoor locations and the power density of solar energy is 1000 times higher than the average of other ambient energy sources. However, in some scenarios, such as night time, cloudy days, and indoor environments, or situations in which solar cells are covered by dust or shadowed by nearby objects, the solar cells do not operate at all or their efficiency significantly decreases. Under such circumstances, other ambient energy sources must be utilized. However, there are limitations, such as low power level availability in the ambient environment and imperfect efficiencies of different harvesters. In addition, the typical energy collected from stand-alone ambient energy harvesters is low to drive wireless sensors. Stand-alone harvesters may also not be able to provide continuous operation due to functional constraints as well as external factors, such as the unpredictable availability of ambient energy sources. Therefore, it is advantageous to combine several ambient energy harvesters into one module to achieve (a) sufficient collected energy to power sensor nodes and (b) continuous operation of sensor nodes so that they can compensate for each other’s limitations.

Several ambient energy sources are available, such as wind, water flow, vibration, waste heat, temperature difference, and electromagnetic radiation, among others. The choice of energy harvesters that are integrated into one module depends on the type of application, location, energy source availability, surrounding environment, and so forth. A considerable amount of research has been done in designing hybrid multi-source energy harvesters to increase the amount of collected energy and address the limitations of single-source harvesters. In a harvester that collects energy from wind, light, and water flow is used to power a data acquisition unit. In a power conversion efficiency (PCE) boost is demonstrated by using a combination of electromagnetic energy (RF) and kinetic energy (vibration) harvesters. Another example of a hybrid harvesting system is presented in, where piezoelectric harvesting and microbial fuel cells are combined to achieve a reliable operation of an underwater sensor network. Furthermore, hybrid harvesters containing different combinations of single renewable energy harvesters are presented in. All the hybrid harvesters mentioned above are dependent on a specific location and source, such as wind, water flow, and vibration, among others. Thus, the limitation of these hybrid harvesters is that they cannot be utilized universally in any environment, as their sources are location specific. In other words, they cannot be used in the circumstances described above (indoors, night time outdoors, poor weather conditions, underground, etc).

Harvesting ambient RF energy and thermal energy has great potential, as both sources are available 24 hours a day and are not location specific. RF energy harvesting can be done through a receiving antenna that can capture electromagnetic signals from available wireless bands and a rectifying circuit that transforms these signals into useful electrical energy. On the other hand, the thermal energy harvester can generate energy from the diurnal cycle (temperature fluctuations in an environment, particularly between day and night time). The available power density of RF and thermal sources can be combined to generate more power to be suitable for IoT applications. An RF energy harvester can be improved by harvesting from multiple available bands at the same time so that output power can be increased. In turn, a thermal energy harvester can be optimized and tuned specifically to the temperature fluctuation of the given environment.

In this paper, we present a multi-source ambient energy harvester that collects energy from RF signals and diurnal temperature fluctuations to power sensor nodes of the IoT (Figure 1). We perform smart system integration by combining RF and thermal energy harvesters into one module without them degrading each other’s performance. The multi-source harvester is characterized in many locations, such as indoor, outdoor, and underground environments. As a proof of concept, we show an IoT application where continuous operation (with certain time intervals) of temperature and humidity sensors is achieved when powered by the multi-source ambient energy harvester.
2.1 | Thermal energy harvester design and fabrication

Transient temperature variations are pervasive in our surroundings, coming from the diurnal cycle, human activity, and exhaust heat from vehicles and computers, among others. However, temperature fluctuation has not yet been exploited as a ubiquitous energy source. A novel device called a thermal resonator for transient thermal energy harvesting has recently been developed.10 The key is to convert temporal fluctuations into a spatial gradient, by having thermal masses with distinct properties on two sides of a thermoelectric generator. Two characteristics distinguish a thermal resonator from previous works: (a) the incorporation of high thermal effusivity ($e = \sqrt{kpC_p}$) materials and (b) the capability of targeting any input frequencies. This leads to a device that generates electricity from broadband temperature variations, requiring neither a static gradient nor a high frequency oscillation. In a thermal resonator (Figure 2A), thermoelectric modules are sandwiched between an aluminum heat fin and a metal foam impregnated with the phase change material (PCM). The PCM is a material that undergoes a phase transition (for example from liquid to solid), which is usually a constant-temperature process, and this temperature is the phase transition temperature. The PCM has much higher effective heat capacity than common materials due to its latent heat (released or absorbed energy during the constant-temperature process). When the thermal energy harvester is operated near the phase transition temperature of PCM, a great amount of heat can be stored or released with very little temperature change. In contrast to the PCM, a heat fin is made of a material with low heat capacity, which will follow the changing environmental temperature closely. This will create a time-varying temperature difference across the thermoelectric generator (white pads in Figure 2A), which can harvest this difference to produce electricity. The high heat capacity of PCM is combined with the high thermal conductivity of a metal foam to create the high thermal effusivity. This characteristic has been shown both experimentally and theoretically to enhance the power density of the thermal harvester.9,10

We first develop an analytical model (Figure 2A) with no flux at the internal boundaries ($\chi_j = 0$) and no heat transfer resistance at the external boundaries ($\chi_j = L_j$). From our previous analytical model in, $^9$ the time-averaged power density ($P_{avg}$) for a thermal harvester subjected to sinusoidal input temperature fluctuations is described as:

$$P_{avg} \approx \eta e_1 T_A \sqrt{\omega Q}$$

(1)

where $\eta$ is the efficiency of the thermoelectric heat engine, as shown in Equation (2), $e_1$ is the thermal effusivity of mass 1, as given by Equation (5), $T_A$ is the amplitude of temperature fluctuations, $\omega$ is the angular frequency of temperature fluctuations, and $Q$ is a tuning factor that is given in Equation (3).

$$\eta = \left(1 - \frac{T_C}{T_H}\right) \frac{1}{\sqrt{1+ZT-1}} \frac{1}{\sqrt{1+ZT+T_C/T_H}}$$

(2)

where $T_C$ is the cold reservoir temperature, $T_H$ is the hot reservoir temperature, and $ZT$ is the thermoelectric figure of merit, which is assumed to be 1 for the commercial Bi$_2$Te$_3$ thermoelectrics used in this work.

$$Q = \frac{1}{8} \left(\text{Re} \left(\text{sech} \left(\sqrt{\nu}i\right)\right) - 1\right)^2$$

(3)

where $\nu$ is the dimensionless frequency:

$$\nu = \frac{L_1^2}{\alpha_1}$$

(4)

$L_1$ is the length of thermal mass 1 and $\alpha_1$ is the thermal diffusivity of thermal mass 1. For PCM, the apparent thermal effusivity due to latent heat is:

$$e_{app} = \frac{\sqrt{kp\rho}}{2T_A}$$

(5)
where $k$ is the thermal conductivity of the material (assume no change in thermal conductivity with phase), $\rho$ is the density, and $h$ is the latent heat per mass.

Thermal effusivity ($e_1$) measures a material’s ability to exchange heat with its surroundings. The comparison between a pure PCM (eicosane, E) and a metal/PCM composite (Ni/E) in Figure 2B exhibits the enhancement of thermal effusivity through the embedded metal matrix. We also construct a numerical model accounting for the heat flux through the thermoelectric modules, and the convective heat transfer at the external boundaries. The numerical model agrees better with the experimental value than with the analytical one. The thermal resonator is optimized to work persistently in a harsh environment, such as the desert of Saudi Arabia.

Ultra-high-molecular-weight (UHMW) polyethylene with the dimensions of $10 \times 10 \times 15$ cm$^3$ is used as a package for the thermal harvester (Figure 3A). A high thermal effusivity PCM composed of eicosane ($T^* = 36^\circ$C; $h = 250$ J g$^{-1}$) vacuum impregnated within a highly porous and highly thermally conducting nickel matrix (Ni/E) is fabricated specifically for application in the desert environment of Saudi Arabia. Eicosane is chosen because its phase transition temperature matches the desired temperature, and because of its high heat storage capabilities. In the first step, the UHMW container is filled with the phase change material (nickel foam and eicosane), as shown in Figure 3B. Four heat engines are sandwiched between two copper plates and placed on top of the UHMW box (Figure 3C,D). The fabricated thermal harvester is displayed in Figure 3E.

2.2 | RF energy harvester design and fabrication

With the rapid development of wireless technologies, there are more electromagnetic waves around us that carry signals from different standards, such as GSM, 3G, WiFi, and so forth. Intense usage of wireless devices and services directly leads to more electromagnetic energy around us, as cell phone base stations radiate electromagnetic signals in an omnidirectional fashion. This ambient electromagnetic energy can be collected and converted into useful electrical energy.

The RF energy harvester consists of an antenna that can capture wireless signals from the ambient environment and circuits (impedance matching circuit, rectifier circuit) and that converts AC signals into DC (Figure 4A). First, an ambient RF power measurement is performed to identify the most powerful RF bands. Measurements are conducted eight times a day in five different locations to obtain information about the time and location dependence. To increase the accuracy of the measurements, cable and reference antenna losses are de-embedded, and the power averaging option on a spectrum analyzer is selected. The result of the measurement shows that the most powerful bands are GSM900, 3G, and GSM1800 in a descending order, compared with other available bands, such as WiFi. This result is considered valid, as most mobile phone operators in Saudi Arabia utilize GSM900 and GSM1800 for calls and 3G at 2.1 GHz for Internet connections. In addition, the maximum output power of GSM900 is more than the GSM1800, which is also

**FIGURE 3** (A) UHMW container of the thermal harvester. (B) UHMW container filled with phase change material: nickel mesh and eicosane. (C - D) Four heat engines sandwiched between two copper plates. (E) Fabricated thermal energy harvester.
consistent with the collected data. The results of the ambient RF power measurement can be seen in Figure S1.

2.2.1 Antenna design and fabrication

To harvest from three bands at the same time, a straightforward approach would be to design three antennas and three rectifier circuits with three matching networks tuned to each of these frequency bands (900 MHz, 1800 MHz, and 2100 MHz). However, this solution is neither cost-effective nor space-effective. Instead, an efficient solution is to design a single rectenna (rectifying antenna) that can harvest from multiple bands simultaneously. For that, a multi-band antenna and a multi-band matching network are required. A fractal approach can be used to achieve multi-band performance, as fractals can provide several resonances due to the combination of different lengths. Fractals are structures with a self-repetitive pattern across different scales. The

fractal pattern used for this project is called a Cantor fractal (Figure 4B). Its pattern is as follows: the first line segment is copied and split up into three parts, and the middle section of those parts is deleted. The same process is reiterated several times to achieve the required multi-band performance.

The antenna is designed using Ansys High Frequency Structure Simulator (HFSS) software by simulating the whole body and inner filling of the thermal harvester to achieve accurate results (Figure 4C). Small pieces of the UHMW polyethylene and inner filling (mix of eicosane and nickel foam), as shown in Figure 4D, are prepared for the characterization in terms of electrical properties. The UHMW is characterized on an impedance analyzer, and a dielectric constant of 2 and loss tangent of 0.02 are measured at 1 GHz. As the UHMW is found to be quite lossy at higher frequencies, we fabricate an antenna on a different low loss material and attach it on the side faces of the UHMW box, instead of printing the antenna directly on the UHMW box. In this way, the effect of the lossiness of the UHMW can be minimized. The chosen
substrate of the antenna is 3D printed Preperm ABS300 material with a dielectric constant of 3 and a loss tangent of 0.004 at 2.4 GHz. Metallization is done through screen printing of silver paste with a conductivity of $10^7$ S/m. All these real values are inserted into the HFSS software for accurate results. The challenging part is to characterize a mix of nickel mesh with eicosane that becomes a homogenous mass and changes its phase from solid to liquid at different temperatures. The measurement of the inner filling through the impedance analyzer does not lead to any result, as the mix has characteristics of both metal and a dielectric. To facilitate the building of the model of the thermal harvester on HFSS, it is assumed that (a) the filling of the box only contains bulk nickel as it is difficult to simulate a metallic mesh and (b) the effect of nickel mesh is dominant compared to eicosane particles affecting the RF performance.

Two Cantor fractals are designed to be the two arms of an antenna. The idea behind the Cantor fractal design of the triple-band antenna is that each iteration is responsible for one resonance. So, three iterations are required to achieve the triple-band antenna performance. Figure 4E-G shows the evolution of the antenna design with different number of iterations and Figure 4H shows the reflection coefficients of these antennas. As it can be seen in Figure 4H, the first iteration’s segment length is optimized to have a resonance at 2.1 GHz (black dotted curve). As at 2.1 GHz the wavelength is 82.5 mm, the length of the first Cantor segment is 82.5 mm. Once the second iteration is added following the Cantor fractal structure (Figure 4F), another resonance appears at around 1.7 GHz (blue curve). The length and width of the small separations between the main segments are important variables to adjust the resonance position so the second resonance can be moved to 1.8 GHz. It is worth to notice that the resonance at around 1.3 GHz is the harmonic of the 2.1 GHz resonance which is also present in the previous black dotted curve of the first iteration.

The third iteration can be added as shown in Figure 4G to achieve the resonance at 900 MHz frequency. Once the
required resonances are in place, the impedance matching must be improved. It is considered an industry standard for the impedance matching when the required band is lower than −10 dB, which implies 90% power transmission to the antenna (see the green line in Figure 4H).

Figure 5A-C shows the current distribution of the antenna at 0.9 GHz, 1.8 GHz, and 2.1 GHz frequencies, respectively. It can be noticed that the high currents are placed in the corresponding iteration segments with respect to frequencies as expected from the design steps. Areas with the high currents are the most sensitive locations for impedance matching and thus, the width of the segments is a valuable parameter to optimize. Figure 5D displays the reflection coefficient for different widths of the segments. As it can be seen from the graph, at 31 mm the resonance at 900 MHz is not quite matched (levels at −10 dB) and at 27 mm, two higher resonances (1.8 and 2.1 GHz) are moved to the right so that the antenna does not work at 1.8 GHz. Therefore, the optimized value of the width must be found where the resonances are at the right frequencies with the decent level of matching. As it can be seen from the graph, the width of the segment must be 29 mm to achieve the best performance.

The antenna of the RF energy harvester is fabricated on 2 mm thick ABS300 substrate with a dielectric constant of 3 and a loss tangent of 0.004. The substrates are printed on a Makerbot Replicator desktop 3D printer. The fractal pattern of the antenna is metallized through screen printing using conductive silver paste from DuPont. The fabricated version of the antenna is shown in Figure 5E. Two parts of the antenna are placed on two adjacent side faces of the thermal harvester box. As one antenna covers only two side faces of this box, we integrate two RF harvesters on the thermal harvester box so that (a) the RF harvester has 360 azimuthal coverage around the thermal harvester and (b) the power collected by the RF harvester is doubled. The final version of the multi-source ambient energy harvester can be seen in Figure 5G. Figure 5F shows the reflection coefficient results of the simulation and measurement in one graph. It can be noticed that the resonances at 1.8 GHz and 2.1 GHz merged with each other and produce one wide bandwidth in measurement. However, green line indicates that the antenna covers all the required bands as the curves are below −10 dB (equivalent of 0.1, power ratio of reflected power to input power) industry standard line which implies 90% power transmission from the antenna to the subsequent circuit. So, it can be concluded that the antenna works well at 900 MHz, 1800 MHz, and 2.1 GHz frequencies and deviation from the simulation results might be caused by the fabrication tolerances. After comparing the simulated and measured results, the previously made assumptions are proven true, as the measured reflection coefficient of the antenna is similar to the simulation results.

2.2.2 Rectifier and matching circuit design and fabrication

To convert the harvested RF power from the antenna to usable DC power for subsequent circuits (sensors, transceivers), a rectifier circuit must be employed. This circuit can be implemented using either CMOS technology18 or the packaged diode. In this work, a single series diode is employed, as this is the best candidate for high sensitivity and minimum diode loss (one diode only). Conventionally, the harvested RF energy generates a small voltage at the output of the antenna. The magnitude of this voltage is in terms of uV, which is unable to turn on a normal diode. Therefore, a special type of diode with high sensitivity must be selected. A Schottky diode SMS 7630-079 from Skyworks19 is chosen since it has low junction capacitance and resistance, low series resistance, and, most importantly, low turn-on voltage. The rectifier circuit is simulated in Keysight Advanced Design System (ADS) software to obtain the input impedance of the diode. The challenge here is that the input impedance of the rectifier varies with the input power level, load condition, and frequency (Figure S2). For example, the input impedance of the rectifier circuit at −20 dB m for 900 MHz, 1800 MHz, and 2100 MHz is 35 - j553, 15 - j274, and 12 - j252, respectively. However, the antenna described in Section 2.2.1 is designed to have an impedance of 50 Ω. To transmit the maximum power from the antenna to the rectifier circuit, the input impedance of the rectifier circuit must be matched to 50 Ω. Therefore, we design a triple-band impedance matching network consisting of four transmission line stubs and two radial stubs. This impedance matching network is different from the triple-band rectifier presented in due to its different substrate and impedance conditions. The layout of the circuit is analyzed and optimized by ADS EM simulation. The circuit board is fabricated using the same combination of 3D printing and screen printing as for the antenna fabrication. Schematic and fabricated versions of the circuit board are shown in Figure 6A,B. The reflection coefficient and rectification results are presented in Figure S3 in the supporting information section.

3 FIELD TESTING AND IOT APPLICATION

Field testing is conducted in three different scenarios to assess the performance of the multi-source ambient energy harvester where one source can compensate for the absence of the other one. The multi-source energy harvester is tested in an outdoor environment, indoor environment, and buried underground. Outputs of each energy harvester are connected to DrDAQ data loggers from Picotech21 where output voltages of the harvesters can be recorded with a certain sampling rate.
In turn, the data loggers are connected to a laptop, where the above-mentioned parameters can be monitored in real time. Measurement is conducted for 24 hours for each of the locations, starting from 9 AM in the morning. The sampling rate is set to 10 seconds to be small enough to capture the changes of fluctuating RF power and large enough for the thermal harvester, as the temperature changes gradually. The output voltage of the RF harvester is collected across a 5 kΩ load, as it is chosen to achieve maximum PCE. Output voltages of the thermal harvester are collected across a 100 Ω load resistance to achieve maximum power transfer, as the internal resistance of the thermal harvester is around 100 Ω. This loading condition is used for all the following measurements in the three different environments.
3.1 | Outdoor environment

Figure 7A shows the measurement setup used to test the multi-source energy harvester in the outdoor environment. The ambient available RF and thermal energy have some patterns, as observed during the pre-design assessment of available power levels. RF energy patterns depend on users’ activity on their mobile phones and 3G internet surfing. In the evaluation stage of the available ambient RF power, we find that users’ activity is highest from morning to afternoon and increases again in the evenings. Early morning hours have the lowest available RF power. In Figure 7B, the same pattern can be observed in terms of output voltage from the RF harvester. Minimum voltage levels are at 100 mV during the whole measurement period, and there are considerable peaks of up to 300 mV from the morning to the afternoon. This happens when active users are close to the multi-source energy harvester or passing by it. Overall, over 24 hours, 105 uWh of energy is collected from the RF energy harvester. Thermal energy depends on the temperature fluctuations during different parts of the day. The pattern is quite consistent (with some exceptions) in Saudi Arabia for a particular time of the year, as can be seen from the historical data.22 The thermal energy harvester shows an output voltage pattern consistent with this pattern. Figure 7C shows that the thermal energy harvester generates the maximum output voltage of 180 mV at around 12 pm because this is the warmest time of day. Output voltage decreases gradually with the temperature drop in the afternoon, and at around 6 pm it starts showing negative output voltage (the ambient temperature is lower than the melting point of the eicosane). Overall, the thermal harvester generates 1200 uWh of energy in 24 hours.

3.2 | Indoor environment

Figure 8A shows the measurement setup used in the indoor environment. As can be seen in Figure 8B, the collected output voltage from the RF source is no less than 100 mV at any time, as in the previous case, and in total it generates 96 uWh of energy in 24 hours. As displayed in Figure 8C, the output voltage of the thermal harvester is around 0 mV and it is almost constant throughout the 24 hours. This result is considered valid, as the temperature of the indoor environment does not change much, remaining constant at 22-24°C. Once the temperature of the eicosane reaches equilibrium with the ambient temperature, the thermal harvester stops generating any output voltage. This test is conducted in Saudi Arabia, where almost all indoor environments (offices, laboratories, etc) are controlled environments through AC. However, there are many places with natural ventilation systems that will have indoor environments with similar temperature trends to the outdoor environment. Thus, in these environments the thermal harvester will operate as in Section 3.1 and will collect energy.

3.3 | Underground environment

In this experiment, the multi-source energy harvester is buried underground (Figure 9A). In this case, the RF energy harvester does not generate any energy (Figure 9B). This is because the soil is lossy and the ambient power level is low, so not enough RF power reaches the RF harvester when it is buried underground. On the other hand, the thermal
The trend of the output voltage is really similar to the one in the Section 3.1 (outdoor environment); however, the scale of the output voltage is different. This can be explained by the fact that the soil is better thermal conductor compared to air and thus the energy collected in 24 hours is expected to be higher in this case as compared to the outdoor environment. At around 12 pm, the thermal harvester shows highest output voltage of 250 mV. Overall, it produces 2300 uWh energy in 24 hours.

3.4 IoT application of sensors powered by ambient multi-source energy harvester

Based on the measured data from the previous sections, the harvested energy is sufficient to power a node in a typical wireless sensor for the IoT network. To verify the utility of the multi-source harvester, we must assess whether it can power up a wireless sensor node for continuous operation. For this experiment, we use a CYALKIT-E02 sensor beacon. This board includes an energy harvesting power management IC (PMIC) S6AE103A, Bluetooth BLE transceiver CYBLE 022, and sensors (temperature and humidity), as illustrated in Figure 10A. On the receiver side, a smartphone with the installed application is used to visualize the readings of the temperature and humidity sensors in a graph.

The challenge here is that the output voltages of the thermal and RF energy harvesters are quite small (a few hundred mV), whereas the sensor node requires 2 V to operate. Therefore, a step-up converter is used to provide the appropriate voltage for the node. TI BQ25504 is selected due to its low input voltage sensitivity of operation (~100 mV). An output voltage of 3 V can be achieved using this step-up converter, with an efficiency of 40%. As stated in the datasheet of the BLE transceiver, the energy needed for one transmission is 200 uJ.
FIGURE 10  (A) Block diagram of the measurement setup. (B) Photo of the measurement setup. (C) Readings from the temperature sensor. (D) Readings from the humidity sensor. (E) Data transmission time interval.
but the peak current needed can be as high as 10 mA, since the transmission time is short (a few milliseconds). To provide such a high current, the harvested energy must be stored in a capacitor in advance. A 1200 uF capacitor is placed at the output of the step-up converter to accumulate the energy. The voltage of this capacitor is charged from 0 V, and the charging time depends on the harvested power, which ultimately dictates the time interval between data transmissions.

Another challenge appears when the voltage on the capacitor reaches 2 V, which is the required voltage of the sensor node operation. The sensor node will attempt to draw the required current (10 mA), but it cannot do this because the capacitor at this instance is not fully charged. When the sensor node draws the current, the voltage on the capacitor will drop below 2 V and the power management IC (PMIC) of the sensor node will shut down the operation. This loop continues, and thus enough energy cannot be collected for one data transmission. To prevent this situation, we need to charge the storage capacitor to a higher voltage (i.e., higher than 2 V) and maintain it above 2 V until enough energy is stored to guarantee one data transmission. This is done by using a switch between the sensor node and the step-up converter. In brief, the switch and the step-up converter are installed in a way that the connection between the sensor node and the harvester is maintained as long as the collected voltage is between 2.8 V and 2.4 V. Below 2.4 V, the switch automatically breaks the connection.

Based on the collection from both RF and thermal harvesters, total 1300 uWh in 24 hours, (Section 3.1), we can calculate the energy generated each second which equals 54.2 uJ. Energy consumption of the BLE for one transmission, as described previously, is 200 uJ. By dividing this value to the energy generated per second from both harvesters, we can achieve data transmission from the sensors after each 3.7 seconds throughout the whole day continuously.

Two assumptions have been made during this calculation which are, (a) power generated from the energy harvesters are evenly distributed throughout the whole day and (b) outputs of the harvesters are combined without any losses (step-up converter losses and etc). Clearly, the distribution of the collected energy throughout the day varies depending on the external factors, so the contribution of the thermal harvester is greater during this particular test (Section 3.1), as more thermal than RF power is collected. However, this situation can be reversed based on another location, where more RF power can be collected as compared to thermal.

As demonstrated in Sections 3.2 and 3.3, there can be situations in which one of the sources is not available, so the IoT sensor node has to operate while powered by a single source. Therefore, in the following we consider two scenarios.

**FIGURE 11** (A) Readings from the temperature sensor. (B) Readings from the humidity sensor. (C) Data transmission time interval
in which only the single thermal harvester or the single RF harvester operates.

Figure 10B displays the setup of the system for the first test, where only the thermal harvester operates. The results of the sensor readings can be seen in Figure 10C,D. As shown in Figure 7C, the power collected from the thermal harvester depends on the temperature fluctuations, so different time intervals achieved between data transmissions, ranging from 8 seconds to 90 seconds, throughout the 6 hours of measurements from 9 AM to 3 PM (Figure 10E). The trend is also very clear that the time interval is small (less than 30 seconds) between 9 AM and 12 PM which can be correlated with Figure 7C where the thermal harvester generates maximum power at the warmest period of day in outdoor environment. In the afternoon, output voltage of the thermal harvester drops gradually which corresponds to the increase in time interval between data transmissions (60 seconds to 90 seconds). In other words, time interval indicates how fast the thermal harvester can charge the capacitor that powers up the temperature and humidity sensors. Overall, average of 29 seconds time interval between data transmissions has been achieved when the IoT sensors are powered by the thermal harvester only. This value is considered as a reasonable time interval as the change in temperature and humidity in such a small time period is negligible. Video demonstration of this experiment can be found in multimedia section of Supporting Information.

From Figures 7B and 8B, it can be seen that the output voltages of the RF energy harvesters vary from 100 mV to peaks of 300 mV. For this experiment, the indoor environment is chosen to test the IoT wireless sensor node when only RF power is available. The results of the temperature and humidity readings from the indoor environment (in this case, an office) are shown in Figure 11A,B. An average time interval of 8 minutes 55 seconds is achieved for the duration of 6 hours (Figure 11C). Depending on the availability of ambient RF power levels, the time interval ranges from 8 minutes 15 seconds to 11 minutes 30 seconds. As the collected power from the RF harvester is lower than that from the thermal harvester (shown in the previous sub-section), the time interval is longer. Even if the output voltages of the thermal and the RF energy harvesters are converted to up to 3 V of required voltage, currents are very different, and the charging of the capacitor occurs more slowly in the RF energy harvester case. However, the conclusion based on this experiment is that when the thermal harvester is off and the weakest energy source is operating, temperature and humidity readings can be achieved every 9 minutes, which still seems to be a decent rate with which to monitor the temperature and humidity levels in an indoor environment. As displayed in Figure 11A,B, the temperature and humidity values are constant over time with minimum fluctuations. This is expected for the indoor environment, as it is controlled by an AC system. In contrast, Figure 10C,D shows that the temperature and humidity of the outdoor environment fluctuate considerably and change gradually over time, depending on the time of day.

4 | CONCLUSION

This paper presented a multi-source ambient energy harvester. The advantage of this harvester is that it can work 24 hours a day in environments where solar energy is not available. It collects energy from thermal and RF energy sources simultaneously. In an experiment, harvesters were smartly integrated into one module, and additive manufacturing techniques were utilized during fabrication. The multi-source energy harvester was tested in three different conditions: indoors, outdoors, and buried underground. The paper also demonstrated a real-world IoT application with temperature and humidity sensors transmitting the data to a phone via Bluetooth.

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section.

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