Research Article

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Energy harvesting for mobile agents supporting wireless sensor networks

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Abstract: Wireless sensor networks (WSNs) have been deployed widely in many different application including in civil and military fields. The sensing data from the networks is very diverse and may cost huge energy consumption for transmission. Hence, mobile sensors with high capacity are deployed to support the static sensors dealing with longer range communicating distances and also supplying power wirelessly the sensors if possible. This paper focuses on an energy harvesting (EH) design for either mobile agents or sensor nodes in WSNs. A hybrid EH system can harvest energy from ambient environment around to power the mobile sensors and static sensors. In addition, these mobile sensors and transfer power wirelessly to the sensors if required. We provide different scenarios for harvesting energy from both RF and solar energy to support the devices. All the designed circuits based on mathematical equations are provided, specifically. Simulation and experimental results are addressed to clarify all the scenarios for the networks. The results show promise and practical.

Keywords: energy harvesting; hybrid RF-solar energy; mobile agents; sensor nodes; wireless sensor networks.

Introduction

Recently, wireless sensor networks (WSNs) facilitate many applications in both civil and military fields (Lai et al. 2022; Pragadeswaran, Madhumitha, and Gopinath 2021). The networks have been researched and developed quite strongly to be able to meet increasing demands of practical applications in harsh conditions. Along with the development of technology 4.0, WSNs are becoming more and more popular and applied in many areas of human life (Kandris et al. 2020). There are many types of sensors to suit many different applications, but we can divide them into two main types: mobile sensors and static sensors (Hutchinson, Oh, and Chen 2017). Static sensors are considered to be small, low cost and low computational capacity (De Freitas et al. 2011), while battery replacement or maintenance for sensor nodes is very complicated. Hence, saving energy to prolong the network lifetime is always a critical issue for such networks.

Multi-media WSNs are in burden of energy consumption since they need to collect and to send high capacity data, such as pictures, videos to a base-station (BS) or a data processing center (Hao et al. 2015; Nguyen, La, and Teague 2015). This multi-media approaches consume more energy from traditional WSNs and make the networks soon to become disconnected since many sensor nodes deplete all pre-charged batteries quickly (Nguyen et al. 2021). There have been many energy efficient approaches to solve the issues of saving energy for such networks. Energy efficient data routing algorithms are proposed including cluster-based (Nguyen and Rahnavard 2013), tree-based (Nguyen and Teague 2014), random walk (Nguyen 2013), etc. to reduce transmitting cost. These methods can be combined with some data processing mechanisms to reduce data transmission that save energy for WSNs (Kim, Jeon, and Park 2013; Nguyen, Teague, and Rahnavard 2014). In addition, some studies and proposals of data processing algorithms to eliminate redundant data in the networks that can reduce the network's energy consumption significantly to prolong the network lifetime (Do et al. 2021). Improving the performance of the battery, as well as reducing the charging time, makes the device operation longer and more efficient as mentioned in the paper (Nguyen et al. 2020; Quyen et al. 2020). Another energy-efficient direction is to harvest energy from ambient environments to power sensor nodes. The sensors can harvest more energy from many resources such as solar,

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vibration, wind, radio frequencies, etc. to support themselves (Tran et al. 2022). However, the harvested energy may not provide enough for sensors in all tasks including sensing and communicating.

Mobile agents or mobile sensors are considered to assist WSNs since they can move to areas that static sensor sensing range may not reach (Nguyen 2020). In addition, they have high capacity to deal with long range communications and also have big recharged batteries to operate. Last but not least, the mobile agents can power sensor nodes wirelessly.

Most of the frameworks about using mobile agents to support the WSNs focus on proposing some devices with low energy consumption, utilizing large-capacity batteries to prolong the life of the device (Gandhimathi and Murugaboopathi 2021; Nguyen and Teague 2015). There is a good chance that the mobile agents can supply and replenish to the battery power from renewable energy sources outside the surrounding environments with their higher profiles compared to sensor nodes. To increase the working time for sensor nodes, we propose to use mobile agents to both collect data and provide power by using wireless power transmission for sensor nodes. When the sensor nodes are within the communication range of mobile agents. Besides, the design of electronic circuits to perform the function of collecting energy, or converting energy is also proposed and designed in this paper.

As mentioned above, the problem of energy in wireless sensor networks is always a very important and concerning issue, it motivates us to propose a system to collect, provide and replenish energy for sensor nodes. In this proposal, we use mobile agents to both collect data and transmit power to the sensor nodes as shown in Figure 1. Therefore, we design a hybrid solar and RF energy harvesting system integrated into each Mobile Robot. With sensor nodes, we only design a system that collects RF energy sources, which are emitted from mobile agents and RF sources from the surrounding environment at a frequency of 900 MHz. The mobile agents will move in a defined trajectory, when ensuring the communication range with the sensor nodes, they will collect data from the sensor sent to them and the mobile agents will transmit energy to the sensor nodes by using far-field wireless power transmission (WPT) technology.

The rest of the article is organized as follows. Problem formulation presents problem formulation. The detailed circuit design for the proposed system is described in Circuit designs. Simulation results shows the simulation results of the charging process for the devices in the systems. Finally, conclusions and future developments directions are outlined in Conclusions and future developments.

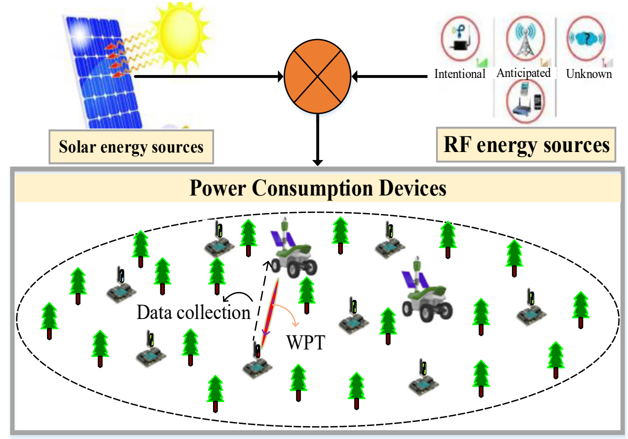

Figure 1: System model.

Problem formulation

In this section, we provide frameworks for both RF and solar energy harvesting mechanisms. The system model is illustrated in Figure 1. In the model, we provide both possibilities for the mobile agents to support WSNs. Two common energy harvesting methods are provided as follows.

RF energy harvesting

Antenna

The antenna is an electronic device that can radiate or receive electromagnetic waves. Its main function is to radiate RF signals from the transmitter as radio waves or to convert radio waves into RF signals for processing at the receiver. Another function of the antenna is to direct radiated energy in one or more desired directions. Each antenna when designed will operate in a specified frequency range, such as antennas operating in the 2.4 GHz, 900 MHz, and 1800 MHz frequency bands. In this paper, we use antennas operating in the 900 MHz frequency band.

Impendence matching

Impedance matching is the use of a matching circuit between the load and the transmission line. The impedance matching circuit is designed so that the input impedance is equal to the impedance of the transmission line. Then the reflection of the wave towards the transmission line is no more.

The goal of impedance matching is to obtain maximum power on the load, minimizing power loss on the transmission line. There are many impedance matching methods such as using waveguides; using focus elements L (inductor), C (capacitor); using $\lambda/4$ coupler; using a multi-segment coupler. In this paper, we use the method of using L, C focus elements to perform impedance matching as shown in RF energy harvesting.

Voltage multiplier

One of the interesting features of this circuit is when these stages are placed in series. The output voltage of the circuit will increase like when we stack batteries in series to get a higher output voltage. Figure 2 shows a voltage multiplier circuit with a stage.

Each independent stage with a voltage multiplier can be considered as a single battery with an open circuit output voltage of V_0.

The output voltage of the voltage multiplier circuit when there are multiple stages (n stages) connected in series will be calculated according to formula (1).

$$V_{out} = \frac{nV_0}{nR_0 + R_L} = V_0 \frac{1}{\frac{R_0}{R_L} + \frac{1}{n}}. \tag{1}$$

where R_L is the load resistance, R_0 is internal resistance, V_{out} is output voltage, V_0 is open circuit output voltage.

Solar energy harvesting

There is only one MPP point for each certain weather condition, moreover, when the weather conditions change, the MPP point also changes. Thus, to optimize the performance of the Solar panel, it is necessary to always keep the Solar panel working at the MPP point. The MPPT (Maximum Power Point Tracker) will perform that task by controlling the opening and closing of the switching valve of the DC/DC converter as shown in Figure 3.

Assume that the PMT plate is connected directly to a pure resistance load as shown in Figure 4.

The working point of the solar panel is the intersection between the I–V characteristic of the solar panel and the I–V characteristic of the load. Considering the pure resistance load, the load curve becomes a straight line with a slope of $1/R$. Assuming there are three values of the load, R_1, R_2, and R_3, the three corresponding I–V curves will have slopes of $1/R_1$, $1/R_2$, $1/R_3$ respectively. Among them, only the corresponding load curve R_2 intersects the I–V curve of the solar panel at the MPP point as shown in Figure 5.

So for a load with an R_2 value, the solar panel will work at the point of maximum power MPP, but this only happens randomly. When the weather conditions change or the load fluctuates, the MPPT unit will work to always track the MPP point based on the principle of load matching.

When the solar panel is directly connected to the load, the working point will be determined by the load characteristics, when the value of the load coincides with the value of $R_{MPP} = \frac{V_{MPP}}{I_{MPP}}$, the power transmitted from the solar panel to the load will be the largest, where $R_{MPP}R$ is the

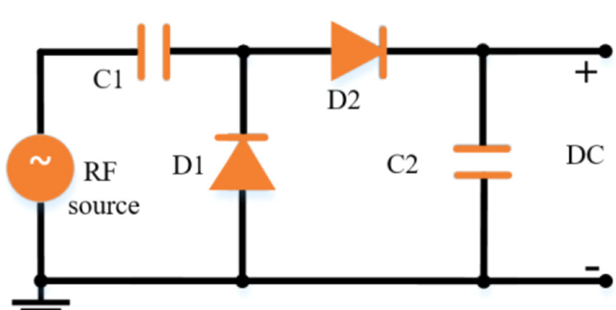

Figure 2: The single-stage voltage multiplier circuit.

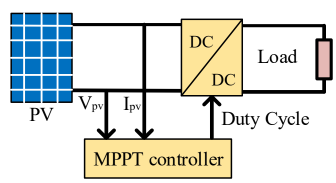

Figure 3: Maximum power tracking controller in solar cell system.

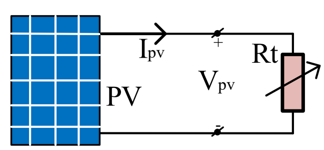

Figure 4: Solar cells are connected directly to the load.

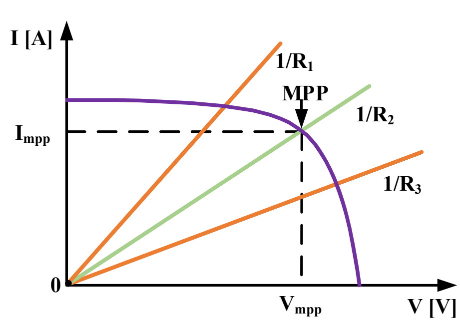

Figure 5: Working characteristics of solar cells and loads.

resistance corresponding to the MPP, V_{MPP} is the voltage at the MPP, I_{MPP} is the current at the MPP.

Among DC/DC converters, Boost converter is widely used. This paper will focus on a boost converter; solar panel system using a boost converter is illustrated as shown in Figure 6.

The relational equations of the boost converter are given as follows:

$$\frac{V_t}{V_{PV}} = \frac{1}{1-D} \tag{2}$$

$$\frac{I_t}{I_{PV}} = 1 - D \tag{3}$$

$$V_t = R_t I_t \tag{4}$$

where V_{PV}: the output voltage of the solar cell (V);

I_{PV}: the output current of the solar panel (A);

V_t: the output voltage on the load;

I_t: the output current on the load;

D: modulation factor of the converter;

R_t: load resistance.

$$V_t = \frac{V_{PV}}{1-D};\ I_t = I_{PV}(1-D) \tag{5}$$

$$\frac{V_{PV}}{I_{PV}} = R_t(1-D)^2 \tag{6}$$

$$R_{td}(D, R_t) = \frac{V_{PV}}{I_{PV}} \tag{7}$$

$$R_{td}(D, R_t) = R_t(1-D)^2 \tag{8}$$

From formula (8), we see that $R_{td}(D, R_t)$ depends on the modulation factor D of the Boost converter and the value of the load R_t. Therefore, it is possible to change the value of R_{td} by varying the modulation factor D.

The operating point of the system is the intersection of the I–V curve of the solar panel and the I–V characteristic of the load, illustrated in Figure 7.

From Figure 7 the tilt angle of the load characteristic is determined as follows

$$\theta_{R_{td}}(D, R_t) = a\tan\frac{1}{(1-D)^2 R_t}. \tag{9}$$

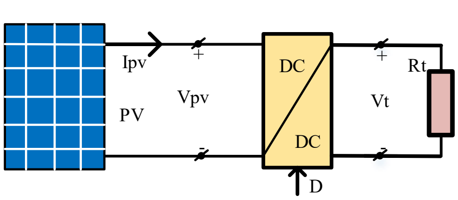

Figure 6: Solar cell connected to load via DC/DC converter.

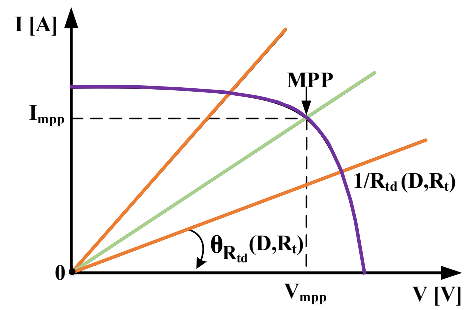

Figure 7: Tilt angle of equivalent load characteristic.

Changing the position of the working point by changing the tilt angle means changing the modulation factor D. A suitable change of D will obtain the intersection of two characteristic curves established at the correct MPP.

Circuit designs

The proposal's detailed structure is depicted in Figure 8, which can be found here. The ultimate objective is to produce a DC power source that can be inserted into the charger in order to charge the battery. To accomplish this, we will have a distinct method and approach to harvest each source of energy. Figure 8 demonstrates that in order to bring the voltage up to the required level of 18.5 V, the solar energy source employs both the MPPT algorithm and the boost converter. The RF energy source is harvested from the environment at a frequency range of 900 MHz, and after going through the converter circuits, a DC voltage of 5 V is obtained, which corresponds to five stages connected in series. The next few paragraphs will walk you through the step-by-step process of designing the system components in minute detail.

RF energy harvesting

Impendence matching

The impedance matching is something that we do in this paper by utilizing elements such as inductors (L) and capacitors (C).

We will assume that the design requirement for an impedance matching circuit is for it to operate at 900 MHz with a source impedance of $Z_S = 50\ \Omega$, a load impedance of $Z_L = 50 - 60j\ (\Omega)$, and a line impedance $Z_0 = 50\ \Omega$. The Smith graph is used as a basis for the calculation of parameters L and C.

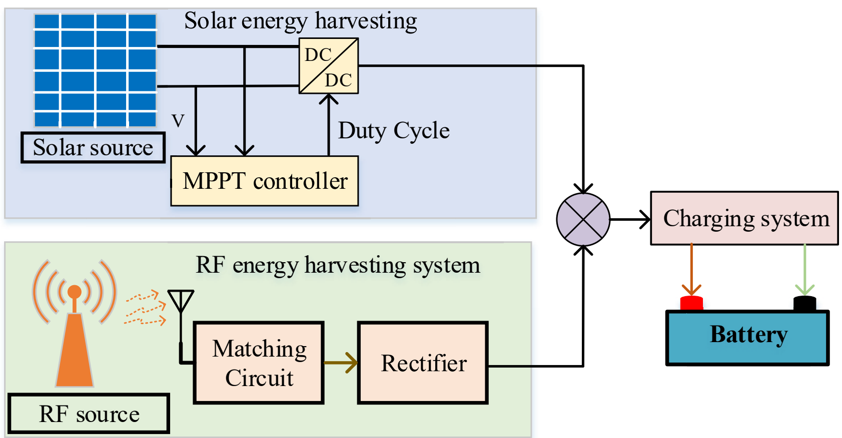

Figure 8: Proposed energy harvesting system.

Based on the information presented in Figure 9, we decide on S-Parameters that have a hop of 0.1 GHz, a starting frequency of 0.1 GHz, and an ending frequency of 2 GHz.

Simulation results show that the resonant frequency at 900 MHz at point *m*1 has a frequency equal to 900 MHz attenuation factor dB ($S(1,1)$ equal to –71.5 dB), at the smith graph, the resonant point at $Z = 50\ \Omega$ with frequency equal to 900 MHz, impedance equal to $Z0*(1 - j5.2E{-}4)$ so the circuit has been impedance matched. The signal from the input goes to the output without loss. According to the smith plot, the impedance obtained at $Z0*(1 + 0j)$ meets the expectation, when the input is combined with the characteristic impedance Z_0 the reflection goes to zero as shown in Figure 10.

Voltage multiplier

Figure 11 shows RF energy passing through an impedance-matching circuit. This energy will then proceed to the next circuit, which is called the rectifiers, where it will be changed from an AC source to a DC source. The number of stages in the circuit is directly proportional to the output voltage. In this study, we use a 5-stage pipeline that is connected in series.

Figure 12 shows the output voltage of the RF energy harvesting system. The output voltage of the circuit depends on the number of stages connected in series in the

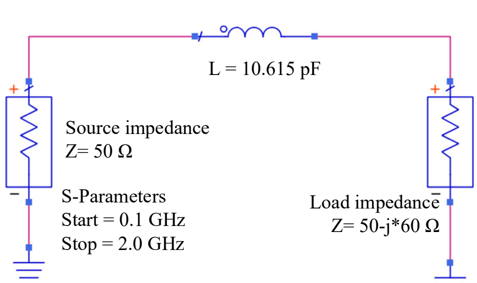

Figure 9: Impedance matching circuit design.

circuit, the black line is the output voltage of the circuit when there is only 1 stage. The output voltage received is 1.43 V and stabilizes after a period of 30 s.

The red line is the output voltage with three stages connected in series in the circuit. The voltage stabilizes at 3.2 V after a period of 30 s. The blue line is the output voltage when the circuit has five stages in series, reaching 5.06 V after a period of 30 s.

Solar energy harvesting

The process of building and simulating the MPPT algorithm is shown in Figure 13.

In Figure 14 displays the power of the solar panel without using the MPPT algorithm as the blue line. The power of the solar panel when using the MPPT algorithm is the red line. We have noticed that when the MPPT algorithm is used, the output power will always tend to fluctuate at the point of maximum power, and the fluctuation range is much less than in the case of not using the MPPT algorithm. This makes the output power more stable. The system output power fluctuates around the peak power point of about 5.6 (W) as shown in Figure 14.

However, the disadvantage of the solar energy system is that it is highly dependent on the surrounding environmental conditions. Therefore, we need to combine with another energy source that is less dependent on environmental conditions, which is RF energy.

Charging system

We built the detailed charging circuit that is shown in Figure 15. The LM317 is an essential element of this charging circuit and was one of the circuits that we designed for it. LM317 is a voltage regulator IC. Pin 1 (ADJ) of the integrated

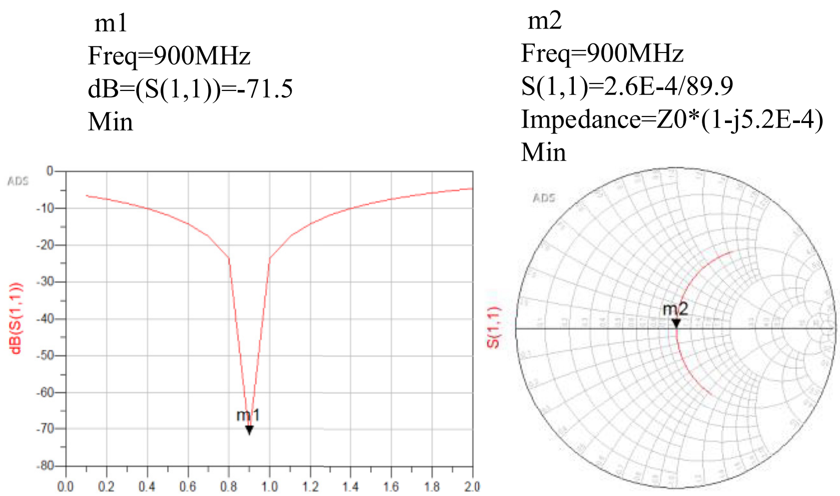

Figure 10: Impedance matching results on Smith chart.

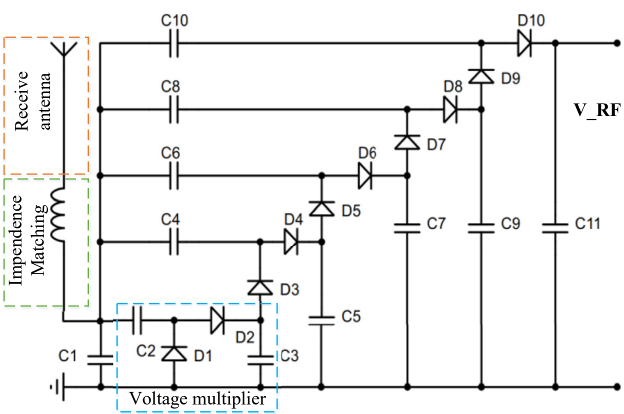

Figure 11: The full multistage voltage multiplier circuit.

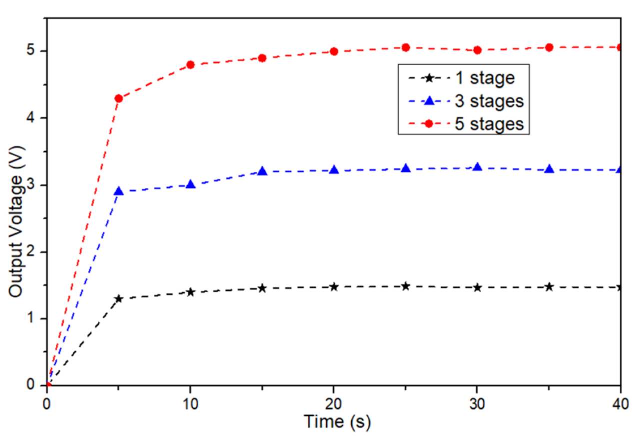

Figure 12: The output voltage of the RF energy-harvesting circuit.

circuit is the control pin, and it is utilized to control the voltage at which the charging occurs. The charging voltage is displayed on the output pin, which is referred to as Pin 2 (VO). The regulated DC supply is connected to the input pin, which is identified by the symbol "VI," which is located on Pin 3. It is possible to adjust the output voltage up to almost 40 V. The LM317 has a voltage that operates between 1.25 and 37 V, it has a maximum output current of 1.5 amps, and its internal resistance can be as low as 0.05 Ω.

Since the LM317 can only produce a maximum output current of 1.5 A. So we have to use transistor Q2 to amplify the current, and as a result, we have a higher charging current, which makes the process of charging the battery go more quickly. The rheostat and the resistor R_2 are responsible for controlling the charging voltage and charging current, respectively.

Simulation results

Charging system for sensor nodes

With sensor nodes, we only use RF power to supply the battery. Therefore, the DC power on the diagram in Figure 16 is currently only derived from the output of the RF energy harvesting system. The charging system for sensor nodes is shown in Figure 16.

With sensor nodes, due to lower energy consumption, we only need to design an RF energy collection system. However, the current is very small, so we have to pass it through the current booster and the charging system to reduce the charging time for the battery.

The charging process is for the sensor nodes, we use a battery with a capacity of 2 A h, the charging current is 1.5 A and the charging voltage is 3 V. The battery starts to recharge when the battery's SoC (State of charge) is ≤50%. The battery's SoC reaches 80% when $t = 3700$ s, and uses the current source (CC charge). SoC of the battery reaches 100% when $t = 4500$ s and uses voltage source (CV charge) as shown in Figure 17.

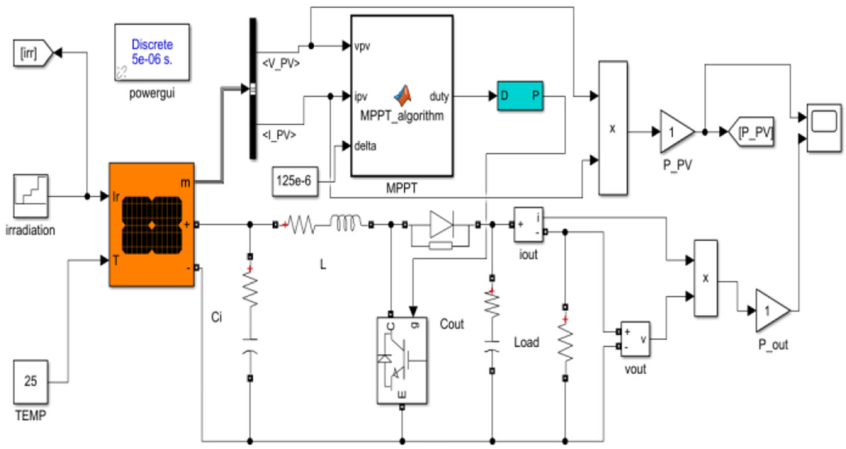

Figure 13: Harvest solar energy using the MPPT algorithm.

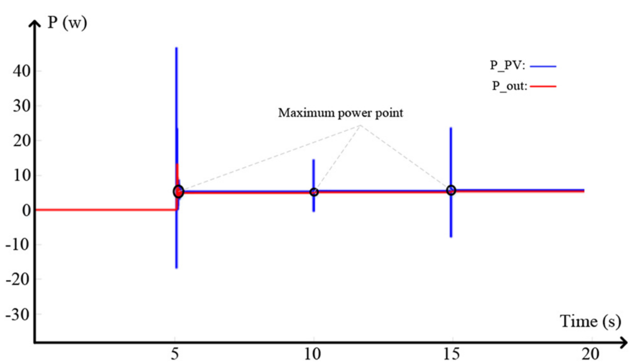

Figure 14: The output of solar harvester circuit using MPPT algorithm.

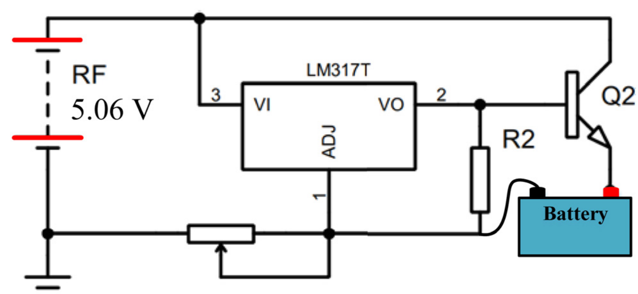

Figure 16: Charging system for sensor nodes.

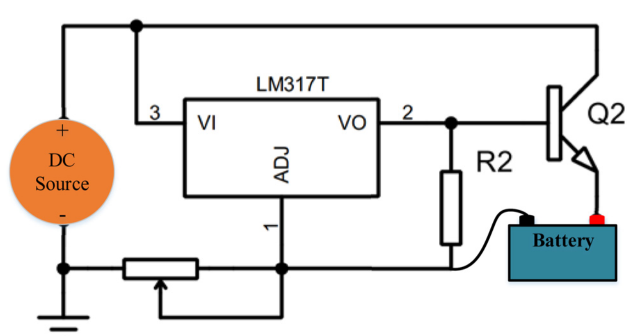

Figure 15: Proposed charging system.

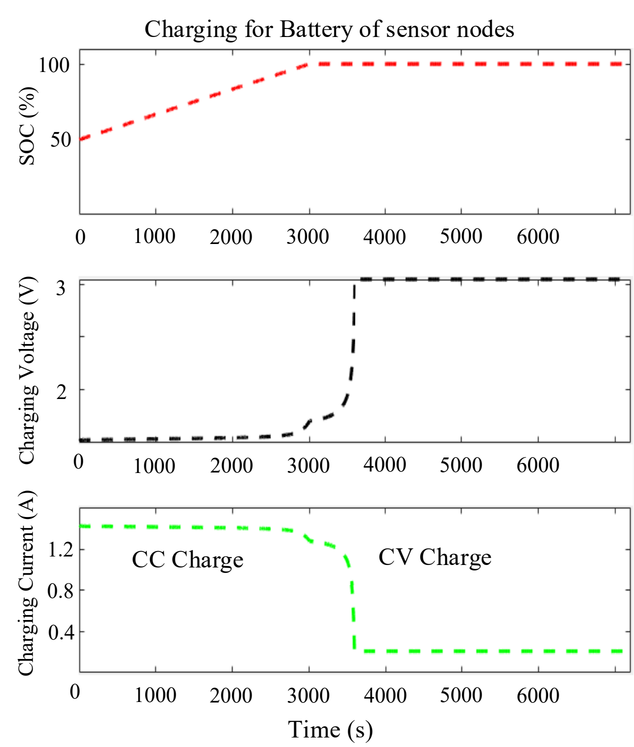

Figure 17: The battery charging process of sensor nodes.

Charging system for mobile agents

In contrast to sensor nodes, our mobile agents use an energy harvesting system that hybrids Solar and RF energy. Mobile Agents require very high charging current and charging voltage, so it is difficult for a single RF power source to meet the charging current requirements. Besides, Solar energy is highly dependent on environmental conditions. So we need to combine these two sources to charge Mobile Agent. As a result, the DC power source depicted in the diagram in Figure 16 will now be replaced by the output voltage of the hybrid RF-solar energy harvesting system, as shown in Figure 18.

The current is 6.8 amps, and the voltage will be 20 V once it has passed through the output of the charging system.

Figure 19 depicts the charging process for devices in the system. We use a battery that has a capacity of 7.66 A h with the mobile robot. The charging current is 6.8 A, the charging voltage is 20 V, and the battery begins to recharge when the state of charge falls to 50%. The procedure for charging a battery consists of two stages: stage one, which lasts from time $t = 0$ s to time $t = 2600$ s and sees the battery being charged by a current source (CC charge). When the SoC reaches 80%, the battery enters the second stage of charging. In other words, this process occurs between the periods $t = 2600$ and 3000 s, as depicted in Figure 19. The phase of charging the battery using a voltage source (CV charge). This phase is necessary for the battery's state of charge to reach 100%.

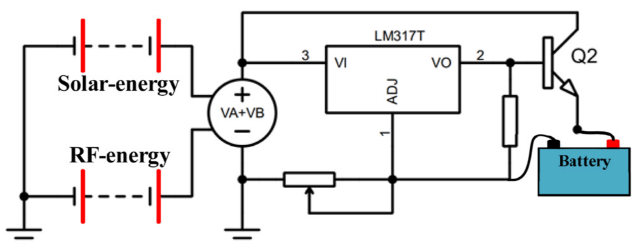

Figure 18: Charging system for mobile agents.

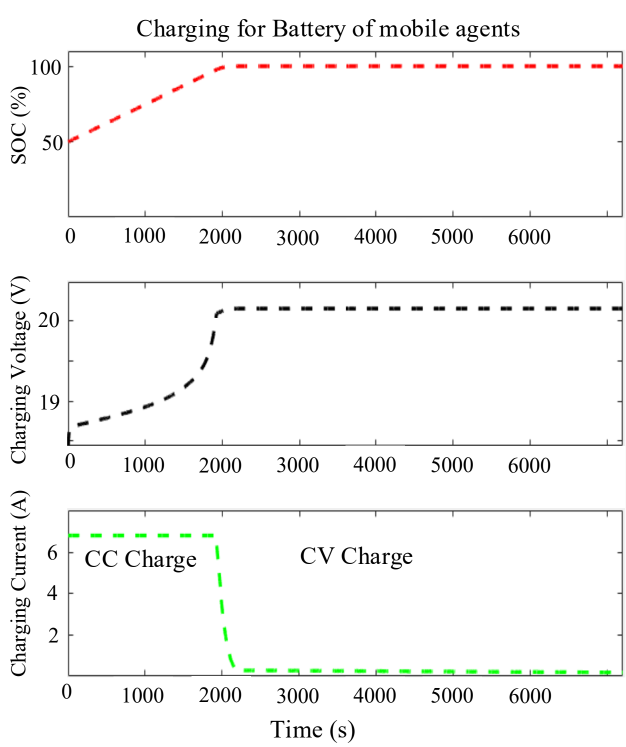

Figure 19: The battery charging process of mobile agents.

Table 1: Comparison results.

Method	V_{Solar}	V_{RF}	V_{Hybrid}	I_{Hybrid}
Jadhav and Lambor (2017)	5 V	5 V	12 V	0.75 A
Singh et al. (2018)	6.1 V	2.24 V	7.8 V	None
This work	18 V	5.06 V	20 V	6.8 A

In Table 1, we make a comparison between the method that we have proposed and some traditional methods regarding the current (I) and voltage (V) of the hybrid energy system, the stand-alone solar energy system, and the stand-alone RF energy system. Our primary focus is on conducting an analysis of the hybrid energy system's parameters. First, with regard to the voltage, it should be noted that all of these approaches are capable of producing output values that are very close to the voltage required by the battery. In regard to the second point, the current, our suggested method achieves the value of 6.8 A, which is significantly higher than the value of 0.75 A achieved by the other methods. As mentioned above, the charging time of the Battery depends a lot on the charging current, so increasing the value of the charging current makes a lot of sense.

Conclusions and future developments

In this paper, we have proposed an efficient energy collection system for devices like mobile agents and sensor nodes. We have detailed design issues with devices with different power consumption to use the power accordingly. Our proposed system can generate a fairly high charging current $I = 6.8$ A. Therefore, it is possible to reduce the charging time for the battery significantly. When the SoC (State of Charge) parameter of the battery drops to 50%, the system will activate the charging process for the Battery. Therefore, the system work can prolong the working time for the devices in the network.

However, in order to improve efficiency in the process of harvesting energy from the environment, we need to pay more attention to improving the conversion efficiency from RF energy to DC. Using new technology such as AI technology in the application of the MPPT algorithm will bring more efficiency.

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