Collecting data in smart cities using energy harvesting technology

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ABSTRACT

This work investigates the problems of extending the sensors network lifetime in smart cities. The limited capacity of the sensors' batteries, and the difficulty of replacing the sensors' batteries in hard-to-reach areas are some of the main challenges that contribute in reducing the lifetimes of the networks. The direction of this study is to use renewable energy as an energy source for collecting data from various infrastructures that are distributed throughout these cities. We present a model for data collection based on combining energy harvesting (EH) with the cluster head rotation feature, which results in flexible and sustainable networks that can be used in smart cities. Simulation results depict the performance of the proposed model with and without EH technology. The metrics used to compare the performance of the proposed model with and without EH technology include the consumed energy by sensors, number of live and dead sensors, and energy variance. The results show that the network lifetime increases when EH technology is used.

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1. INTRODUCTION

Using internet of things (IoT) [1], [2], fifth generation (5G) technology, and cloud computing, we can connect different devices to the Internet. In 2020, it is expected that the number of devices joining the IoT is more than 20 billion devices. Smart cities are the trend of future urban evolution, where IoT plays an important part in implementing such cities [3]–[5]. Sensors are devices used in implementing smart cities, which are embedded into the infrastructures. In IoT, sensors are utilized to connect different types of infrastructures to the internet, which makes the vision of implementing smart cities come true. A large amount of data is collected and processed through large number of networks, where the processed data offers a scientific tool of decision-making enabling intelligent management and development for smart cities.

Developing micro-processing technology enables sensors to have stronger computation power, which makes them adapt to various types of applications. One of these applications is to implement smart cities. There are lots of sensors deployed in smart cities to control the infrastructures by collecting data by these sensors [6]. In smart cities, the sensors are used for collecting the environmental data, traffic data, surveillance data, and different types of data. In smart cities, the data collected by sensors are transmitted to the responsible municipal apartments, to manage the infrastructures. The collected data in smart cities helps solve different kinds of problems such as urban pollution, traffic management, and so on. Although sensors can be deployed quickly and flexibly to implement smart cities, collecting data sensed by the sensors is a challenging problem, where the collected data in smart cities is unlike the traditional widely used wireless sensor networks (WSN) [7]–[9].

Most of the former WSN schemes have examined a connected network composed of a number of sensors and a sink, where the sensed data by sensors is routed to the sink via multi-hop communications. However, sensing networks in smart cities work differently compared with traditional WSNs [10]–[15], where sensing networks in smart cities contain large number of sensors, and there is not even a basic communication for connecting with the internet. So, these networks may be described as various isolated WSNs that contain numerous sensors in smart cities [16]. Although those networks can be organized as connected networks, they only contain ordinary nodes without sinks for connecting to the internet. Dedicating fixed nodes to collect data from many temporary networks is inefficient in terms of time and cost. These collecting data schemes can only be used in a single WSN, but they cannot be used to collect data for many isolated networks.

A data collection scheme was proposed using mobile vehicles and opportunistic communication in [4]. This idea depends on observing that there is a huge number of mobile vehicles moving in cities [17], [18]. In this scenario, the sensors that are close to the road act as sinks, and opportunistic communication of mobile vehicles is used for collecting data in smart cities. The suggested idea in [4] is considered as a tool for collecting data via mobile vehicles, where these vehicles can collect data efficiently due to the availability of mobile vehicles in smart cities. Energy harvesting (EH) is among the efficient solutions providing sustainable wireless networks. EH wireless networks is introduced to implement communication nodes that are capable of recharging their batteries via different natural sources, and exploit this energy for transmitting data [19].

Current EH technology is capable of providing limited amounts of energy, for example, outdoor solar panels can take advantage of 10 mW/cm^2 solar energy flux with harvesting efficiency that varies between 5% and 30%, based on the material utilized in the solar panels [20]. Simultaneously, cooperative communication is considered as one of the developed wireless communications technologies [21], [22], such that the wireless nodes can help each other in transmitting and receiving their data to get more reliable communication systems [23]. Integrating EH technology and cooperative communication can obtain a reliable communication system. An EH with cooperative communication system was investigated in [24]. It was assumed that both the rely and the source are EH nodes. The relay harvests energy from radio frequency signals. The goal is maximizing the throughput via optimizing the transmission power.

A paper to enable IoT for wireless sensor networks was presented in [25]. The proposed model was subjected to a black widow optimization (BWO) technology that seeks to effectively select cluster heads, and was subjected to an oppositional artificial bee colony (OABC) based on routing process in order to choose the optimal paths in the process of transmitting and collecting data. The method is called cluster-based routing-information centric wireless sensor networks (CBR-ICWSN). This method achieved results in terms of lifetime network and energy efficiency that outperformed other techniques. The implementation scheme of WSN in IoT was proposed, which is a cryptographic-based digital architecture that aims to maintain data privacy and network power routing used in data aggregation and multi-hop communication based on optimal privacy-multihop dynamic clustering routing protocol (OP-MDCRP) form in order to reduce power consumption, number of nodes and increase network life in [26].

In our work, we investigate collecting data challenge in the sensing network in smart cities using EH technology. The importance of this type of data collection challenge appears in using EH communications to reduce the cost, and to prolong the network lifetime. The remainder of the paper is organized is being as. In section 2, the system model is presented. Experimental results are presented in section 3. Finally, section 4 presents the conclusions.

2. SYSTEM MODEL

In this context, it is assumed that the network contains many EH sensors, where the overall network is splitted up into a number of isolated WSNs. The considered network is described is being as:

- EH sensors: the sensors are distributed in the smart city, where they are used to detect a phenomenon in the city, and send the data about this phenomenon to the vehicle once they satisfy a condition. These sensors are able to harvest energy from the environment and store it in a finite battery. It is considered a time slotted system, where the time slots have equal duration of T_c. The harvested energy is harvested and stored in the batteries as an integer multiple of a basic unit. Assume that the maximum capacity of the used batteries is B_{max}. Let B_k represent the battery level of the sensor at the onset of time slot k. In this considered model, some sensors are assigned as cluster heads (CHs) from the available sensors, that have a direct communication with the vehicles. The other nodes, which have enough energy for transmitting data, send their data to the CHs to transmit the data to the vehicles.

- Mobile vehicles: they are vehicles traveling between the roads in smart cities. These vehicles are able to receive the collected data by the sensors deployed in the city, and then forward the data to the central unit. These vehicles exchange data with nodes and transmit it to the data center using short-range communication based on opportunistic communication. The vehicles do not follow predefined routes; they are driven based on the need of the driver.
- Central unit: it is responsible for receiving and analysing collected data by the mobile vehicles and it is located at a predefined location.
- Energy recharging model: The EH sensors in this context follows the following model: each sensor is provided with a solar panel with an area of 5 cm^2 with harvesting efficiency that equals 5%. The solar energy flux varies between 0 and 10 mW/cm^2 based on the weather and the location of the sensors.
- Energy consumption model: the consumed energy in this context follows a common energy consumption model [14], where a sensor consumes E_t energy to transmit l bits of data from hop h to hop (h+1), which is given by:

$$E_t = \begin{cases} L * E_e + L*K_{fs}* r^2, r<r_0 \\ L * E_e + L* K_{amp}* r^4, r\geq r_0 \end{cases} \quad (1)$$

where E_e is the consumed energy by the circuit of the transmitter, K_{fs} and K_{amp} are the needed energy for power amplification in the free space model and the multipath model, respectively, and r is the transmission distance between the transmitter and receiver. The power amplification loss uses the free space model if the transmission distance is less than the threshold r_0, while the multi-path model is used when the transmission distance is greater than or equal to the threshold r_0.The consumed energy by each sensor resulting from receiving l bits of data is calculated by:

$$E_r = L * E_e \quad (2)$$

3. METHODOLOGY

In this section, we present the suggested scheme for data collection using EH to prolong the lifetime of the network of the WSN in smart cities. The proposed scheme consists of four stages: the preparation stage, the CH rotation stage, multi-hop path selection stage and finally, the stage of transmission and data collection using EH. In the preparation stage, the WSN is divided into four separate networks that are distant from each other, where each network consists of a number of nodes. The number of nodes in each network varies from network to another, where the nodes are distributed randomly among the available networks. In general, we have a number of vehicles deployed in smart cities, which integrate with receiver and transmitter chips that can communicate with sensor nodes and the center of data when they pass throughout the roads. Four vehicles are used, where each two vehicles are placed on the same road. Figure 1 shows the components of a WSN network. After that, the stage of selecting the multi-paths for transmitting data begins. After determining the CH nodes, the parent node of the nodes in each network is determined for determining the path for each node for transmitting data to CH. Finally, the data transfer phase using EH begins. Figure 2, shows the proposed model flowchart.

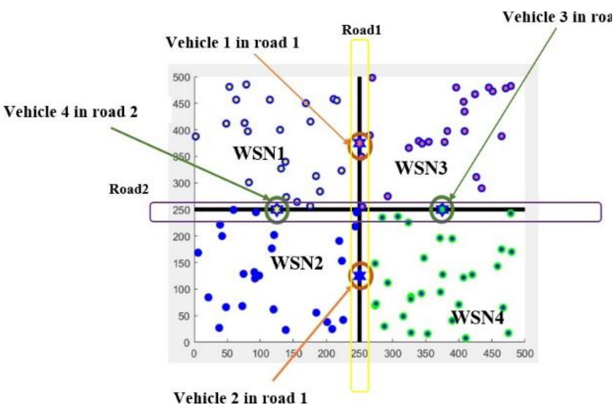


Figure 1. The components of a WSN network

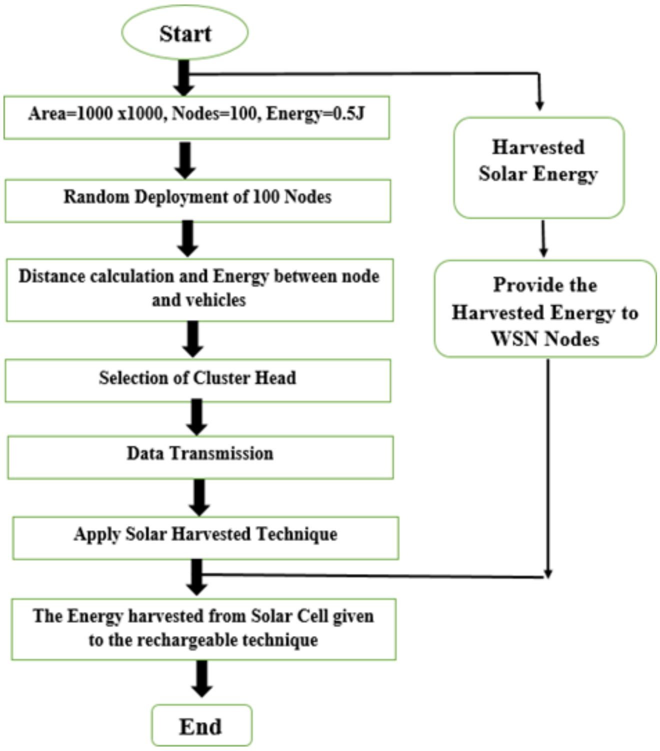


Figure 2. The proposed model

3.1. Preparation stage

In this stage, we build a WSN with an area of 1000×1000 m^2 and divide it into four isolated networks, after which four vehicles are deployed along the roads. The nodes and vehicles can determine their locations using the global position system (GPS). Each vehicle seeks to determine the hops' number between its location and the nodes through sending signals to the nodes. The nodes which receive these signals and fall within the communication range are considered to have a hopping distance of 1. This process is repeated until all nodes know a distance hopping between them and the vehicles, the nodes with hop distance 1 re-publish messages to other nodes, so the nodes receiving this message become with a hop distance of 2 from the vehicle, this process is repeated until all nodes determine their hopping distance from the vehicle. Figure 3, illustrates the hop distance process.

After that, the stage of determining the CH nodes begins. This stage is considered one of the most important stages since CH nodes are the most energy consuming nodes. In our model, we have four networks; each network should have a CH, which is determined based on the distance between the vehicles and the nodes. After the process of determining the hop distance between the nodes and the vehicles is completed, the vehicles in turn select CH by considering that the nodes with hop distance 1 will be the candidates to be CH nodes.

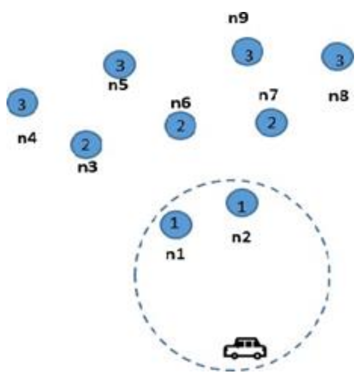


Figure 3. Hop distance

3.2. Cluster head rotation stage

After completing the selection process of the candidate CHs, we select the appropriate CH depending on a combination of factors, namely distance and energy, given the energy consumption constraints imposed by the distance between vehicles and nodes. Due to the presence of more than one candidate CH, we should take into account the energy of the candidate CHs in the selection process. We choose the node with the largest residual energy due to the large amount of consumed energy by the CH nodes during transmitting data, where the principle of CH rotation will be applied in every round.

In each round, it depends on the selection of a new CH based on the remaining energy at each node in addition to the distance between the nodes and the vehicles. We calculate the cost function that depends on the distance between the nodes and the vehicle, and the remaining energy of the node, since it is the most influential factor in the process of CH selection. The cost function and the factor of energy are calculated is being as:

$$q_{dis} = \frac{dis(n_s,v_c)}{\max(dis(n_s,v_c))} \tag{3}$$

$$q_{eg} = \frac{1-eg(n_s,v_c)}{\max(eg(n_s,v_c))} \tag{4}$$

$$c_f = \alpha q_{dis} + (1-\alpha) q_{eg} \tag{5}$$

where $dis\ (n_s,v_c)$ is the distance from the vehicle to the nominated CH node, $max\ dis(n_s, v_c)$ is the maximum distance value, while $eg(n_s)$ is the remaining energy (n_s) and max $(eg(n_s))$ is the maximum energy value). From that point onward, CH will be selected as the node with the minimum cost in every WSN network. The energy consumption of the nodes is affected by the amount of data it transmits and delivers to CH, in addition to the distance between the nodes and the vehicle, and CH nodes consume large amount of energy since they transmit the greatest data amount, hence, we try to reduce data excrement using the technology of data compression, which will be explained in the following subsection. In every round, the CH is rotated, where the residual energy in each node and the distance between nodes and the vehicle are used in the process of CH rotation.

3.3. Multi-hope path selection stage

We begin the process of defining the path that each node takes to transfer its data. It is necessary to determine the least expensive path to send data. Initially CH (hop distance is 1) broadcasts a message that it is the parent node, then the nodes within the range of CH node communications receive it and CH determines that it is the parent node, then nodes that selected CH as the parent node broadcasts a message that it is the parent node, received by nodes within the communication range, and determines that it is the parent node. The process is repeated until all nodes have selected parent nodes and are able to specify their path to CH for data transmission. It is possible that more than one message will end up at the same node, so it is necessary to find the optimal parent node based on the distance and remaining energy of the candidate CH nodes.

For example, suppose that there is a source node (n_s), with a hop distance (h_i), and the parent node (n_p) need to be specified for it, a message from the nodes with a hop distance (h_i -1) is received by the source node, which is a candidate parent node, maybe it receives more than one message from more than one node (n_p), hence, in this situation, the parent node must be selected at the minimum cost by relying on the factor of distance and residual energy factor. The source node with the minimum transmission distance is determined, by calculating the shortest distance between a parent node, source node, and vehicle, in addition to calculating the lowest energy that may be utilized for the path between the parent node, source node and vehicle, depending on the energy of the candidate parent node, correspondingly selecting the parent node that has the lowest distance and the highest residual energy. Figure 4 explains the procedure of selecting paths, as we understand for example that node 5, can choose either node 3 or 6 as a parent node, because of the equal distance for the two nodes, however, we notice that it picks node 3 as a parent node since the remaining energy at node 3 is higher than the energy at node 6. The values of the factors of residual energy, distance, and cost function are calculated is being as: the residual energy factor is:

$$q_{eg}(s,p) = \frac{1-eg_{min}(n_s,n_p,v_c)}{max\ (eg_{min}(n_s,n_p,v_c))} \tag{6}$$

$$q_{eg}(s,p) = \frac{dis(n_s,n_p,v_c)}{max\ (dis(n_s,n_p,v_c))} \tag{7}$$

$$c_f\ (s,p) = \alpha q_{dis}(s,p) + (1-\alpha) q_{eg}(s,p) \tag{8}$$

3.4. Energy harvested from solar cell stage

EH is one of the methods that can be used to reduce the need of replacing batteries, and this is what encourages us to use it in smart cities in addition to increasing the lifetime of the network. Solar cell is based on the principle of EH due to its ability to be recharged depending on sunlight, which makes it a renewable and unlimited source of energy due to its continuous renewal. The solar cell is the harvesting unit used in solar EH. The solar cell is able to convert light rays into electrical energy that can be used by WSNs. Scientifically; each solar panel requires a basic photovoltaic (PV) system that includes a number of solar cells that produce electricity. Generally, WSN decade, the solar energy harvester, consists of a solar panel a direct current-direct current (DC-DC) converter, a rechargeable battery and power management circuits. Figure 5 shows a model of a solar energy harvester.

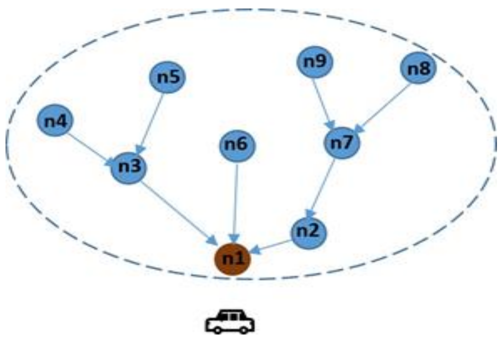


Figure 4. Paths

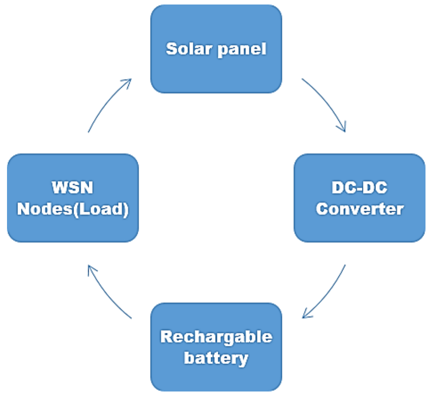


Figure 5. Solar energy harvester model

4. EXPERIMENTAL RESULTS

In this section, our proposed system is evaluated, where MATLAB is used to simulate the network. The network size is 1000×1000 m^2 and 100 sensors are randomly deployed in the network. Table 1 shows the used parameters in the simulation.

Table 1. Parameters of simulations

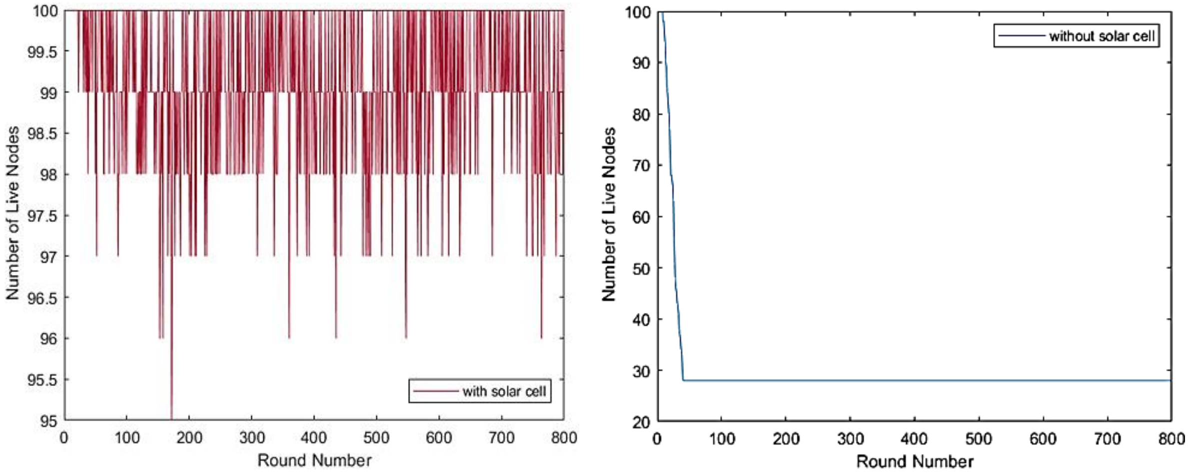
Parameter	Value
Network area	1000×1000 m^2
Number of sensor nodes	100
Threshold Distance (m)	87
Sensing node (m)	<80
Initial energy (J)	0.5
$E_{ele}(nJ/bit)$	50
$\epsilon_{fs}(PJ/bit/m\hat{}2)$	10
$\epsilon_{amp}(PJ/bit/m\hat{}2)$	0.0013
Data packet size (bit)	100
Send packet size (bit)	1000
Node Distribution	Randomly
α	0.3
Solar cell energy(J)	0.1

4.1. Simulation results

In this part, the proposed network is evaluated using two scenarios. The first one is when the deployed sensors are conventional sensors, where they are equipped with conventional batteries used for transmitting and receiving data. In the second scenario, the used sensors are EH sensors. These sensors are capable of harvesting solar energy and convert it into electric energy to be used for transmitting and receiving data. Four metrics are used to evaluate both scenarios, which are the live nodes number, the dead nodes number, the total nodes energy, and the energy variance.

4.1.1. Live nodes number

Figures 6(a) and 6(b) show the number of live nodes per each round for both scenarios (i.e., using EH sensors and using battery-powered sensors). It is clear that the number of live nodes using EH sensors is greater than the number of live nodes using battery-powered sensors, which is due to recharging the batteries of EH sensors. This also shows the effectiveness of using EH sensors, which results in prolonging the network lifetime.

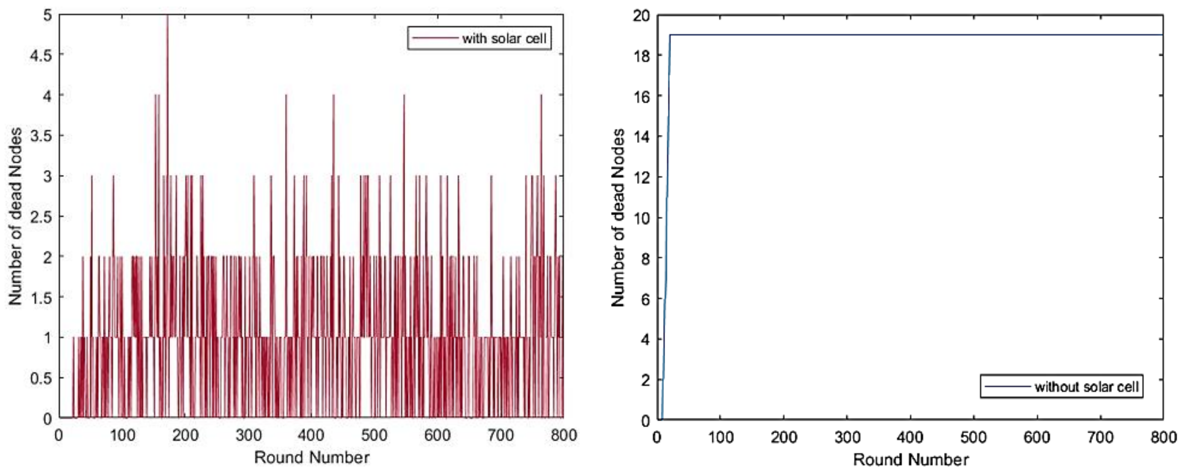


(a) (b)

Figure 6. Number of live nodes (a) with energy harvesting and (b) without energy harvesting

4.1.2. Number of dead nodes

Figures 7(a) and 7(b) depict the dead nodes number per every round when the network consists of EH nodes and when it consists of battery-powered sensors. It can be noted that the dead nodes number in the EH network is less than the dead nodes number in the conventional network. This means that the EH network can cover more areas compared with the conventional network, which also means longer lifetime of the EH network compared with the other network. Figure 7(a) also shows that the number of dead nodes varies with time, which is due to the change of the available solar energy with time. This highlights an important property of the EH network, which is the ability to reactivate dead sensors, which is unavailable in conventional networks. Figure 7(b) shows that the sensors in the conventional network start dying early, especially for sensors that are selected to be cluster heads, which is due to high energy consumption required for processing the transferred data.

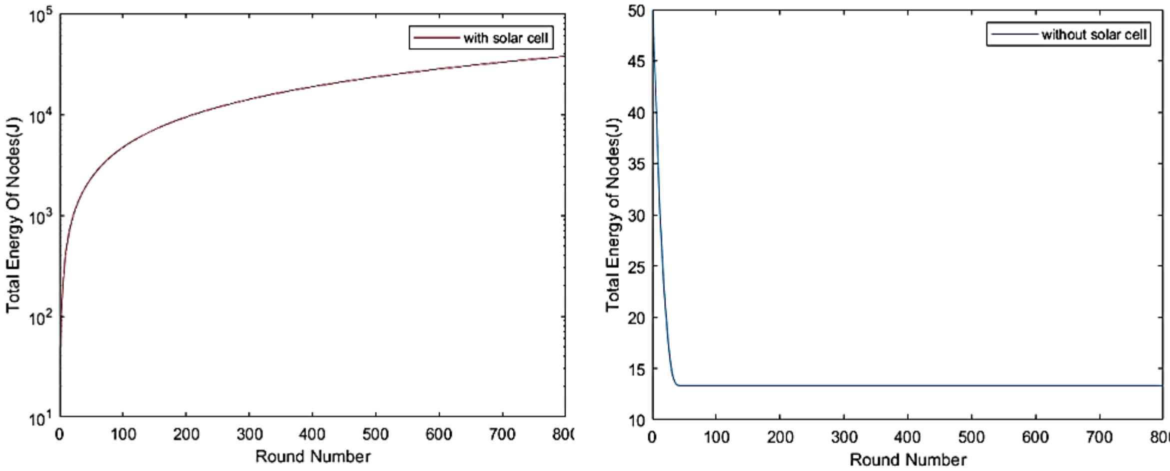


(a) (b)

Figure 7. Number of dead nodes (a) with energy harvesting and (b) without energy harvesting

4.1.3. Total energy of nodes

Figures 8(a) and 8(b) show the instantaneous amount of energy available in both EH network and the conventional network, respectively. It can be clearly seen that the instantaneous amount of energy in the conventional network is less than the energy in the EH network all the time. This can be explained by the fact that the sensors in the EH network are able to compensate the consumed energy by harvesting energy from the environment, which is unavailable in the conventional networks.

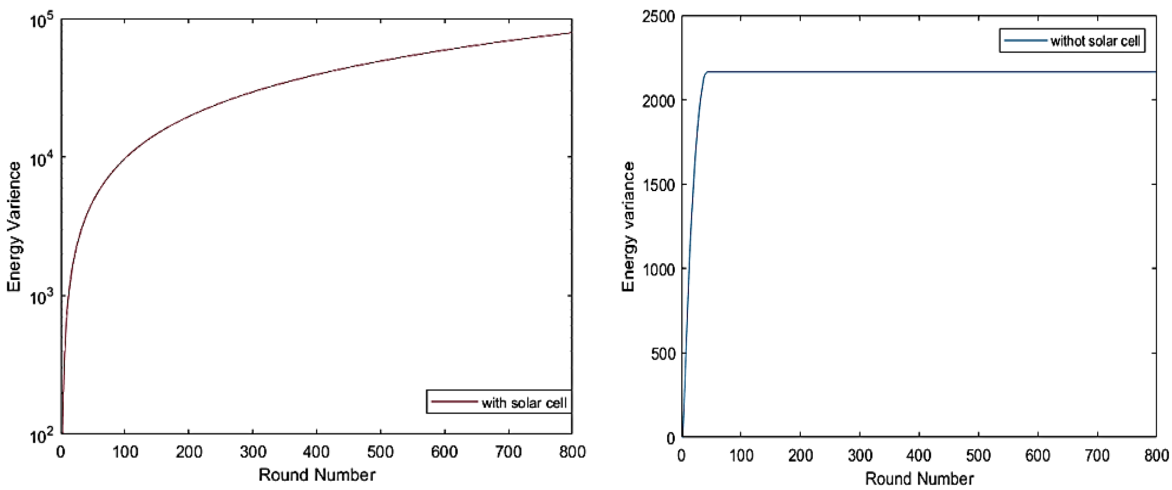


(a) (b)

Figure 8. The instantaneous amount of available energy for nodes (a) with energy harvesting and (b) without energy harvesting

4.1.4. Variance of energy

The variance of energy represents the difference between the minimum and the maximum energy. Figures 9(b) and(b) represent the energy variance for both EH network and conventional network, respectively. The energy variance of the EH network is greater than the other network.



(a) (b)

Figure 9. Energy variance for nodes (a) with energy harvesting and (b) without energy harvesting

5. CONCLUSION

In this paper, we presented a model for collecting data in smart cities using mobile vehicles, where sensors use EH technology as a source for energy. We divided the sensor network in the smart city into various isolated and independent WSN, where every network has a one CHs that is chosen depending on a cost function. This cost function is a function of the distance between the CHs and the vehicle, and the remaining energy in each node every round. Our main idea is to use EH technology to provide the WSN with energy that enables the network to extend its lifetime. We verified the proposed idea by comparing the network performance with and without using EH. The results show the superiority of the network assisted by EH technology in terms of extending the network lifetime and achieving better performance.

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