

Energy Harvesting Routing Algorithms for WSN-based IoT Environment

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Abstract – The Internet-in-Things (IoT) is a network infrastructure containing large number of uniquely identifiable things or objects that are interconnected through the internet. These day to day physical objects are also connected to the sensors, for receiving the information from objects. This structure allows them to communicate with each other without any human interaction, thus forming a heterogeneous WSN. This IoT network depends on the wireless sensors; a massive amount of data is collected by the sensors and communicated to specified locations over the network. The lifetime of the network and communication process is purely based on the energy sources of the objects and applications.

Energy consumption is one of the major issue in WSN based IoT applications. The researchers and developers have always regarded this issue as a challenge for WSN based IoT environment. The IoT sensors continuously require energy to receive and communicate to remote locations of the IoT network, but the main resource of power is the battery. Efficient Energy Harvesting techniques could remove the needs of frequent energy source replacement, thus offering a near perpetual network operating environment. Thus, energy harvesting is the best solution to retain the lifetime of the sensors and the network.

In this paper, our primary focus is to study energy harvesting performance in WSN based IoT applications, in order to increase the availability of the sensors and retain the lifetime of the network. We also discuss a new routing algorithm EHARA, which has been further enhanced by integrating a new parameter called 'extra backoff'. This algorithm improves the lifetime of sensor nodes as well as the quality-of-service (QoS) under variable traffic load and energy availability conditions.

Keywords - Energy, Objects, Harvesting, IoT, Sensors, Wireless, Network.

1. Introduction to IoT, WSN and its EE

Internet of Things (IoT) is an intellectual network of the unique detective devices that are interconnected, and capable of communicating wirelessly with others, services, and the large number of people on the Internet, to perform complex tasks in cooperative manners. The functionality of IoT extends to "anytime" and "any place", and already, "anything". The Internet-of-Things (IoT) is a recent Information and Communication Technology (ICT) paradigm for the distributed embedded computing and communication systems.

IoT is now widespread, and has the ability to affect many aspects of users' quality. In the year 2020, it is estimated that 26 to 50 billion items will be linked to IoT, which is larger than all current Internet programs, which are connected to smart phones. As already calculated, currently 200 people per person can be linked to IoT, which will lead to hundreds of billions of communications devices. Internet of Things (IoT), or devices connected to the Internet, third, and large bandwidth are rapidly developing in cyberspace. In 2020, IoT 2820 billion Internet connections are expected to connect in 2020, with more than a billion users accessing the net by accessing personal computers or two billion users on phones and tablets. However, IoT's neglected feature is a potential increase in power consumption. IoT devices are generally expected to be accessed through other devices at all times.

Many IoT edge devices are operated by the battery. Some early estimates of global battery consumption and associated productivity have also been made, to estimate the proliferation of the associated edge devices, and evaluate the impact of IoT applications prior to global energy consumption.

Recently, IoT applications based on heterogeneous Wireless Sensor Network (WSN)

architecture have been attracting a significant attention from the research community. By enabling easy access and interaction with things or objects, the WSN-based IoT paradigm has been finding applications in many domains, such as Smart Home, Smart Health-care, Smart Transportation, Smart City and Smart Grid

WSN is typically used to monitor environmental or geographical location for some specific purpose. WSN consists of sensor nodes that have the capability of self-configuration and their deployment in target area is easy. The sensor tracks the data stored by the consoles by transferring the data between the other sensor terminals. During the transfer process, when the multihop routing is over, the data tracked by the system may be monitored several times and can finally go to the management point of the Internet or satellite. A WSN is generally described as a single network, which controls the unity and the environment, helping to communicate between persons or computers and surrounding situations. Currently WSNs usually include sensor nodes, actuator edges, gates, and client. However, WSNs have some limitations including battery power, data rates, memory, and processing.

Many routing protocols have been proposed for traditional homogeneous WSNs, wherein sensor nodes have the same capabilities in communications, power, processing, sensing, and storage capacity. The Internet-of-Things (IoT) applications of WSNs, are based on a heterogeneous WSN architecture. In this case, heterogeneity of WSN architecture and the energy harvesting capability from diverse operating conditions are considered. Heterogeneity could be considered from the initial energy, energy consumption, residual energy, link capacity, sensing capacity and even transmission range. In practice, traditional routing protocols for homogeneous WSNs are unable to adapt to the flexibility in heterogeneous WSNs. Therefore, it is essential to develop routing protocols for heterogeneous WSN-based IoT applications.



Figure 1: - The remaining battery levels at sensor node

While not in use, most devices enter a wait state, which uses considerably less energy. Even billions of such devices have raised concerns over

excessive wait power consumption, even if they have moderate power requirements. Thus low power consumption of equipment becomes one of the major technical challenges.

Energy efficiency (EE) and energy availability are critical issues in wireless sensor networks (WSNs). Beside energy-efficient MAC protocols, developing efficient routing protocols is critical for the development of energy harvested multi-hop WSNs. The principal objective of routing protocols is not only to transmit data from a source to a destination, but also to perform this function in an energy-efficient manner to maximize the lifetime of the WSNs

In recent developments in wireless sensor networks, one of the most widely known popular research topics in literature is the energy harvest. Advances in energy conservation techniques have shifted the design of routing protocols for EH-WSN from 'energy-aware' to 'energy-harvesting-aware'. Energy harvesting (EH) is emerging as a proposal for field-deployable WSNs and IoT applications. To deal with the energy base problem in WSN, energy harvesting technology can be used to harvest energy from the network environment, and various protocols and algorithms are used to ensure continuous operation of the WSN based IoT applications. This paper aims to study various energy-harvesting-aware routing protocols for heterogeneous WSN-based IoT applications in the presence of ambient energy sources.

Energy harvesting (EH) is considered to be the key-enabling technology for the mass deployment of wireless sensor networks (WSNs) for Internet of Things (IoT) applications. Using the EH techniques, sensor nodes can extract energy and recharge their batteries during operation. Energy harvesting networks allow fixed battery-less operation, making it very important for a sustainable 'near-perpetual' WSN operability.

Thus, Energy Harvest-based WSNs can be used by the power of different forces, such as solar power, wind, engine vibrations, temperature variations, and magnetic fields. However, the challenges that energy harvesting poses, include developing the mechanisms for obtaining electricity and harvesting power from various sources as well as storing the harvested energy.

2. Architecture for EH-WSN Based IoT

The architecture shown, illustrates the block diagram of an Energy Harvesting Wireless Sensor Network (EH-WSN). Energy Harvest and Energy Storage Devices generate energy

harvesting power management systems extended to the lifespan of the terminal network, for energy and / or future use.

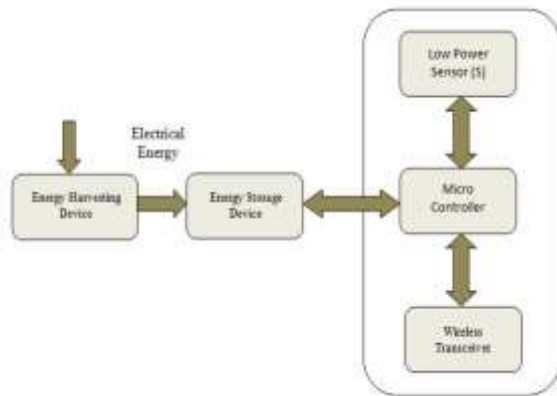


Figure 2: - Architecture of EHWSN

The IoT is an intelligent network infrastructure wherein a large number of uniquely identifiable things or objects (e.g., sensors, actuators and wireless devices) are interconnected to perform complex tasks in cooperative manners. Networking devices connected to IoT architecture are generally sensors, controller processors, wireless transceivers and an energy source (E.g. battery) to monitor their environment and receive / receive data.

As the most representative member of IoT, Wireless Sensor Network (WSN) can be described by a three-tier structure (shown in Fig. 3). The bottom layer consists of a large number of scattered sensor nodes. The middle layer includes wireless access nodes (Sink), common access , as shown in Fig. 1. The nodes have wire-less connectivity and harvest energy from ambient energy sources. The data sink is powered by an unlimited energy supply. In this model, the nodes can be either a sensor or a router. As a sensor node, it generates a data packet to transmit to the sink, and as a router it forwards the packet to the sink via the links that connect sensors and routers. A sensor can operate as a router to assist other sensors in forwarding packets to the sink.

that allow WSN terminals to be permanently or to nodes (AP) and high-end sensor nodes. The top layer is converged by WSN-related applications. The availability of wide range parameters, such as temperature, air quality, pressure, light, etc. enables WSN to serve as a general platform for many domains.

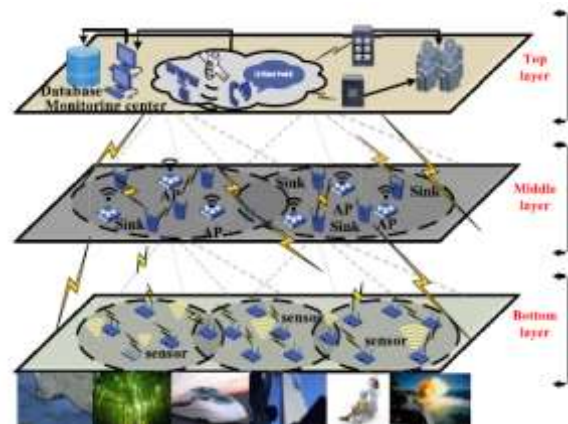


Figure 3: - Three-Tier Architecture of WSN-IoT

The sections followed, will describe the typical architecture for WSN-based IoT applications, in the presence of EH techniques, and present models of energy consumption and energy prediction, used for EHWSN-based IoT applications.

2.1. Network Model

We consider a heterogeneous multi-hop WSN composed of nodes and a sink

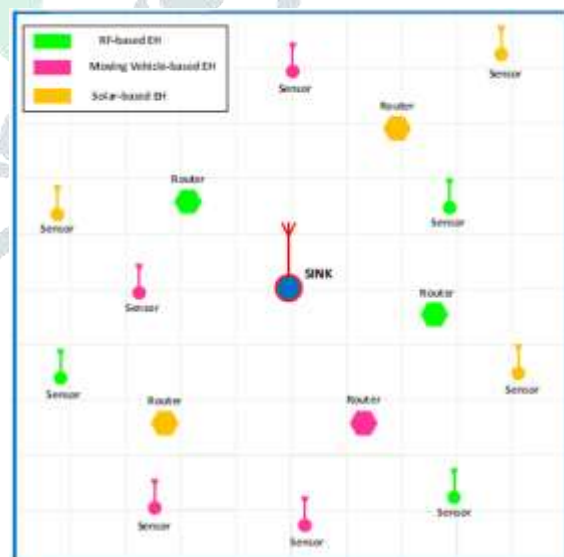


Figure 4: - Network Model of Heterogeneous Multi-hop WSN

In this work, we consider three typical renewable energy sources, such as: solar, vibration (i.e., moving vehicle) and RF radiation. All nodes can harvest energy from one of these sources with different arrival energy harvesting rates. As shown in Fig. 4, the colors of orange, pink and green

represent nodes powered by the solar-based EH, the moving vehicles-based EH and the RF-based EH, respectively.

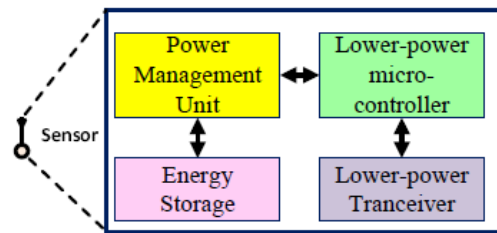


Figure 5: - Node's Configuration

the incoming energy, we consider the harvest-store-use protocol that allows a node to store electricity energy. If the harvested energy is higher than the node's energy consumption, the excess energy will be stored for later use.

2.2 Energy Consumption Model

In order to design an effective routing protocol, it is necessary to determine the energy consumed by each node to process a packet. This energy consists of the energy required to transmit, receive or forward the packet on the selected path. In addition, the node has to expend energy to listen for an arrival packet or wait for an incoming event. In the IEEE 802.15.4-based WSNs, the media access control (MAC) sub-layer will control nodes to enter into these above operating modes.

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3. EH Routing Algorithms

Energy harvesting is one of the hot issues of IoT. Various energy harvesting algorithms exist to reduce the energy consumption of the IoT based network. The harvesting process and the existing approaches are listed below.

3.1. Energy Harvesting Process

Although the energy sources stated in II-A may provide unlimited energy over an infinite period of time, only a limited amount of energy can be obtained at any particular time. To increase the can significantly reduce their consumed energy and accumulate a small amount of energy to prolong their lifetime.

Specially, we introduce an extra backoff process represented by a new parameter of 'extra backoff'. The purpose of this process is to extend the backoff period in the traditional IEEE 802.15.4 CSMA/CA, thus allowing nodes to have more time to wait and harvest energy from the ambient energy sources. Since this process is similar to the backoff technique used in the CSMA/CA protocol to avoid contention, it is compatible with the current CSMA/CA protocol.

The extra backoff process is executed in every B BIs. After B BIs, the node determines its own consumed energy in the B current BIs, $E_{c,cur}^i$. It then calculates

As described in Fig. 5, all sensors and routers have the same configuration, each of which includes a low-power micro-controller for data processing, an IEEE 802.15.4-based low-power RF transceiver, a power management unit, an energy harvester and an energy storage device (e.g., battery). To manage

amount of harvested energy, in this work, the energy harvesting prediction and energy harvesting process will be conducted in a sufficient long period, for instance, in every B Beacon Intervals (BIs).

Considering the battery levels at sensor nodes, we assume that the node's battery can be partitioned into three levels and two regions as shown in Fig. 1. Depending on the node's residual energy E_r^i , we investigate the following two cases:

1) Case 1: $Level < 3E_r^i < Level 2$

Node i will harvest energy during the sleeping period t_{sl}^i . The amount of energy harvested at node i is calculated as:

$$E_h^i = t_{h,h}^i = t_{sl,h}^i;$$

where t_h is the harvesting time and i_h is the energy harvesting rate at the node i . The value of i_h is obtained from the energy harvesting prediction using the KF.

2) Case 2: $0 < E_r^i < Level 3$

In this case, there may not be enough energy for the sensor nodes to maintain their normal operations. Hence, the node has to temporarily turn off its transceivers and enter into the sleeping mode to save energy as well as to wait for a recharge until the battery level is recovered

(i.e., higher than Level 3). By doing so, sensor nodes

the time required for the 'extra backoff' process in the next B BIs as follows:

$$t_{bo}^i = \frac{E_{c,cur}^i}{\lambda_{h,pre}^i} \times \frac{1}{p_{es}^i},$$

where $\lambda_{h,pre}^i$ is the energy harvesting rate at the node i in B previous BIs and p_{es}^i is the probability of the arrival harvested energy from one of three energy sources connected to node i .

The process of 'extra backoff' treats the energy harvesting processes of the nodes powered by the heterogeneous energy sources with fairness, thus contributing to extending the network lifetime.

The harvesting time and the amount of harvested energy at node i are respectively given by:

$$t_h^i = t_{bo}^i + t_{st}^i, \\ E_h^i = t_h^i \lambda_h^i = (t_{bo}^i + t_{st}^i) \lambda_h^i.$$

3.2.EH-WSN Routing Algorithms

In the literature, the energy-harvesting-aware routing algorithms try to assign a cost to each communication link between any two nodes, and then select the link with least cost to transmit data packets to the destination.

Randomized Minimum Path Recovery Time (R-MPRT)

Lin et al. introduced the *Energy-opportunistic Weighted Minimum Energy (E-WME)* algorithm and compute the cost for each sensor node using the available energy and the energy harvesting rate. This work was then developed as the Randomized Minimum Path Recovery Time (R-MPRT) algorithm and assigns each link a cost. The R-MPRT-mod algorithm is the modified and improved version.

In R-MPRT-org algorithm we define the cost function by using the packet energy and harvesting rate of transmitter. Whereas, the R-MPRT-mod algorithm is the modified version of the R-MPRT-org algorithm. In this, instead of using harvesting rate of transmitter, it uses available energy of transmitter, to calculate the cost.

The study of R-MPRT proposed the *Distributed Energy Harvesting Aware Routing (DEHAR)* algorithm, which calculates the shortest paths to the sink using hop counts and available node energy. For EH awareness, the algorithm assigns each node a local penalty which is dynamically updated and inversely proportional to the available energy of the node.

Distributed Energy Harvesting Aware Routing (DEHAR) Algorithm

It is the Communication and Distribution Rounding of EHWSNs, which calculates the availability of narrow paths and capacities on the hop number. In order to add awareness to the power harvest for the algorithm, a local chain is assigned to each point.

This fine, dynamically updated, is the opposite of the separation of energy available to the node. When the node power buffer is fully charged, this fine must be zero, while the node should be endless when it reduces its energy. When a tip is caused by a change in local sentences, it promotes its immediate neighbors.

At each end, the local penalty is attached to the distance from the sink, which is to define the node's energy distance, which is used when the possibility of relay selection by other terminals. If a node changes the neighbor's penalty due to variations in the availability of its energy, the power of a terminal becomes a local minimum. To solve this problem, distributed penalties are introduced.

Energy Harvesting Aware Ad-hoc On-Demand Distance Vector Routing Proto-col (AODV-EHA)

The authors of DEHAR developed the *Energy Harvesting Aware Ad-hoc On-Demand Distance Vector Routing Proto-col (AODV-EHA)*. This algorithm inherits the advantages of the existing AODV in dealing with WSN's ad-hoc nature, and uses the energy harvesting capability of nodes to determine routes with the least transmission cost.

Energy Harvesting Aware Ad hoc On-Demand Distance Vector Routing Protocol(AODV-EHA) that not only inherits the advantage of existing AODV in dealing with WSN's ad hoc nature, but also make use of the energy harvesting capability of the sensor nodes in the network, which is very meaningful to the data .

Energy Harvesting Aware Routing Algorithm (EHARA)

This energy-harvesting-aware routing protocols, is designed for heterogeneous WSN-based IoT applications in the presence of ambient energy sources. This routing algorithm, EHARA is further enhanced by integrating a new parameter called "extra backoff". The algorithm improves the lifetime of sensor nodes as well as the quality-of-service (QoS) under variable traffic load and energy availability conditions.

The algorithm addresses the issues of EE, quality-of-service (QoS) and network lifetime extension in the presence of the EH techniques. In particular, the EHARA selects the best routes using a cost metric that is based on a combination of the consumed energy, the harvested energy and the residual energy at nodes

Algorithm 1 - EHARA.

1. An arrival packet from node i needs to be forwarded
2. Compare E_r^i and Level 3
3. Execute Alg. 1 if E_r^i is in the Case 2
4. Find: $C_{min} = \min (C_{i,j}; C_{i,k})$ 8i; j; k 2 V
5. Forward data packet to the destination
6. Update the routing table in every B BIs
7. Repeat

3.3. Difficulties in Existing Approach

Although the aforementioned routing algorithms can reduce the energy consumption and extend the lifetime of the sensor nodes, they still have their own inherent limitations. For instance, E-WME and DEHAR do not consider the actual amount of harvested energy accumulated during the harvesting period. DEHAR and AODV-EHA use constant rates of replenishment for all sensor nodes in the network. Thus, they cannot deal with the stochastic characteristics of the ambient energy sources. In addition, the routing table used to forward packets in E-WME and R-MPRT is relying on global network state information. In heterogeneous WSNs, however, the global information is unable to adapt to variations in sensor nodes' energy levels (e.g., residual, consumed and harvested energy). Thus, building the routing table with local information in a

distributed fashion should be considered in order to determine routes or links with information from adjacent neighbors. However, EHARA is different from the other existing routing protocols, that addresses the issues of EE, quality-of-service (QoS) and network lifetime extension in the presence of the EH techniques.

4. Results and Performance Evaluation

We consider a data-gathering simulation model using a multi-hop WSN-based IoT network as illustrated in Fig. 4, wherein V heterogeneous sensor nodes are randomly deployed in a region of $100\text{m} \times 100\text{m}$. We assume that all nodes can harvest energy from one of three typical renewable energy

sources, that is, solar, vibration (i.e., moving vehicle) and RF radiation. In this section, we compare the performance of EHARA algorithm with the R-MPRT-mod algorithm and the AODV-EHA algorithm. These routing algorithms can be evaluated by standard measurements such as packet delivery rate, overhead, delay, throughput and energy.

Performance Measurements: The routing algorithms must address performance measurements such as increasing the packet delivery rate and decrease efficiency, decrease delay, and power consumption of the wireless sensor network.



4.1. Throughput:

This is the rate of data packets successfully provided for seconds in the network between targets.

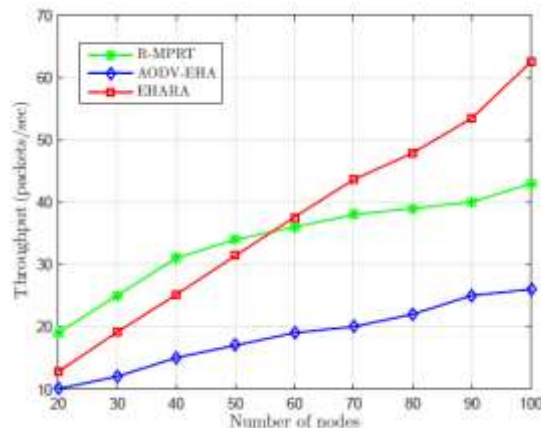


Chart 1: - Throughput - QoS comparisons

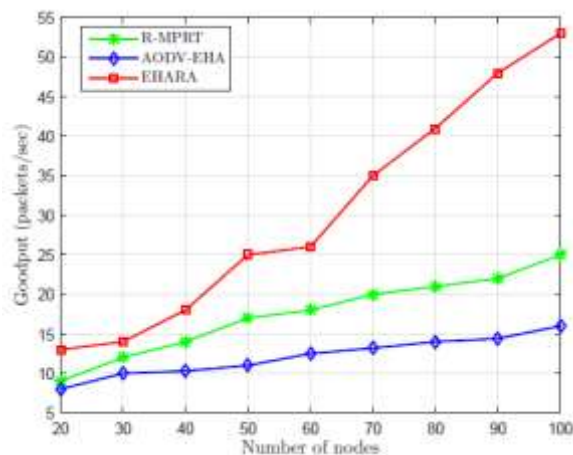


Chart 2: - Goodput - QoS comparisons

4.2. End to End Delay:

This is the time taken by data packets for transmission between targets across the wireless sensor network. This interval is caused by a delay in transmission, suspension, and transfer in MAC.

4.3. Packet Delivery Ratio:

This is the ratio between packets generated between packets received.

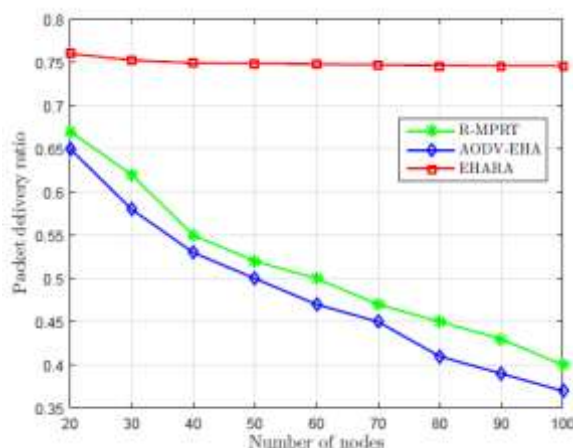


Chart 3: - Packet Delivery Ratio (PDR) - QoS comparisons

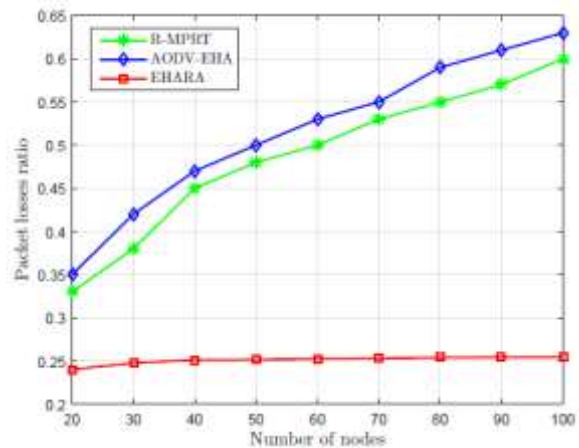


Chart 4: - Packet Losses Ratio (PLR) - QoS comparisons

4.4. Overhead:

This is calculated by the ratio of the total number of control packs sent by the sources to the number of data packets successfully distributed.

4.5. Energy:

This is [the ultimate energy = start-up energy - consumed energy].

We have done our research analysis in wireless sensor networks by using NS2. Comparative analysis done between proposed system and existing system. Now two matrices are evolved and remaining parameters would be found in the future.

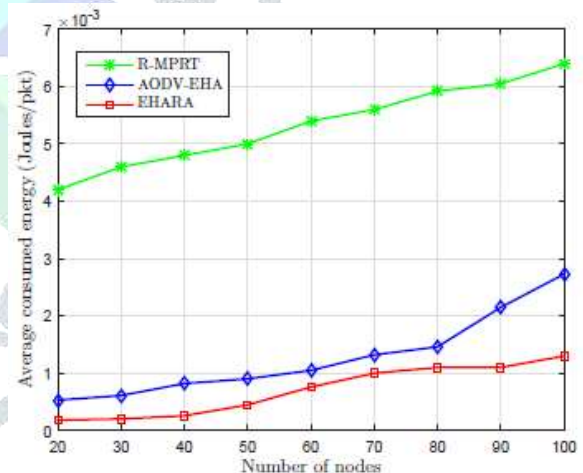


Chart 5: - Average Energy Consumption- EE metrics comparisons

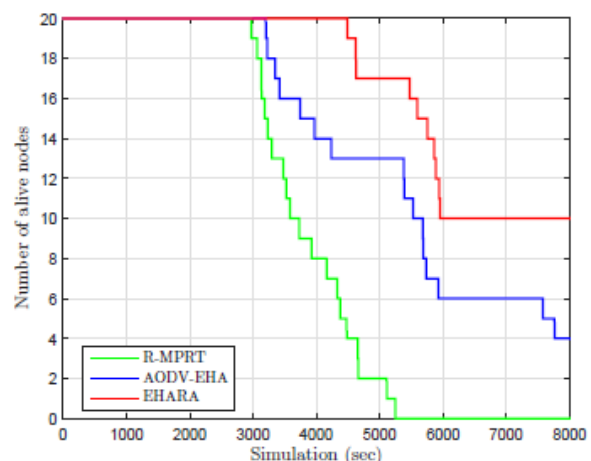


Chart 6: - Alive Nodes - EE metrics comparisons



The performance metrics are EE (e.g., consumed energy per packet and residual energy) and QoS (e.g., throughput, packet loss ratio and packet delivery ratio).

The simulation model is developed in MATLAB environment. In the simulation, the 802.15.4 CSMA-based MAC is employed. To evaluate the EE and QoS, we focus on a special case wherein the remaining battery level transits from Region 2 (approximately 6%) into the region under Level 3 (5%).

In charts 1, 2, 3 and 4 we compare the QoS performance of EHARA, R-MPRT-mod and AODV-EHA algorithms at different values of the total number of source nodes (i.e., sensors).

Chart 1 presents the throughput measured at the sink. At the highest value of source node (i.e., $V = 100$), the AODV-EHA algorithm offers the lowest throughput, only 41% of the EHARA's throughput.

Note that the network throughput is defined as the rate of data packets, including duplicate packets received by the sink. Because the duplicate packets are not useful for the sink, our simulation considers goodput (G) which is defined as the rate of unique packets received by the sink. As shown in Chart 2, the EHARA algorithm outperforms all other algorithms under consideration while maintaining the higher goodput for all values of V .

Chart 4 shows that the network packet losses ratio (PLR) increases with more source nodes. Compared to R-MPRT-mod and AODV-EHA algorithms, the algorithm EHARA achieves better results, where it reduces the packet losses ratio by 60% over that by the AODV-EHA algorithm at $V = 100$ nodes. This is because the EHARA algorithm can maintain the stability and the reliability of the routing table by increasing the number of alive nodes (as shown in Chart 6). As explained above, this allows the EHARA algorithm to improve the packet losses ratio.

In contrast to the PLR metric, in the simulation, we also consider the packet delivery ratio (PDR). This metric computes the probability of a packet being delivered to the sink for every packet transmitted by the source node. As illustrated in Chart 3, for $V = 100$ nodes, the algorithm EHARA introduces the highest package delivery ratio, up to 75% compared to 35% and 40% by the algorithms of AODV-EHA and R-MPRT-mod, respectively. Significantly, the EHARA algorithm maintains the PDR advantage in all conditions of the source nodes V .

Chart 5 compares the average energy consumed by a node using different algorithms. As can be observed, the R-MPRT-mod algorithm expends most energy while the proposed algorithm EHARA consumes the least amount of energy. Because the proposed algorithm EHARA reduces the average consumed energy at each

node, it can increase the number of alive nodes. As seen from Chart 6, after 8,000 seconds, there is 50% of the total nodes to be alive (i.e., 10 nodes) offered by the EHARA algorithm, compared to 20% of that (i.e., 4 nodes) by the algorithm of AODV-EHA.

5. CONCLUSION

In this paper, we have considered the issues of EE and QoS in a combined manner for IoT applications in the presence of three energy harvesting techniques: solar-based EH, RF-based EH and moving vehicle-based EH.

We have discussed an effective routing algorithm, referred to as EHARA, to address the function heterogeneity in heterogeneous WSN-based IoT applications

Simulation results show that Energy-Harvesting-Aware Routing Algorithm (EHARA) outperforms the existing Randomized Minimum Path Recovery Time (R-MPRT) algorithm in terms of network lifetime by about 50%. It also extends the network lifetime by 40% compared to that offered by the existing Energy Harvesting Aware Ad-hoc On-Demand Distance Vector Routing Protocol (AODV-EHA) algorithm.

Simulation results also demonstrate that the proposed EHARA significantly improves energy efficiency while satisfying the QoS requirements of distributed IoT networks in comparison with existing routing protocols.

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