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HYREP: A Hybrid Low-Power Protocol for Wireless Sensor Networks

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ABSTRACT

In this paper, a new hybrid routing protocol is presented for low power Wireless Sensor Networks (WSNs). The new system uses an integrated piezoelectric energy harvester to increase the network lifetime. Power dissipation is one of the most important factors affecting the lifetime of a WSN. An innovative cluster head selection technique using Cuckoo optimization algorithm has been used in the designed protocol. The residual energy of the nodes and the distances to the sink were used in the threshold calculations, besides taking advantage of the relay node for communication. A hybrid method using the optimized routing protocol and the integrated energy harvester results in 100% increase in the network lifetime compared to recent clustering-based protocols. The simulations results using MATLAB indicate that energy consumption has been decreased by more than 40%.

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NOMENCLATURE

$T(n)$	Threshold value in LEACH protocol	l	Number of bits for communication
P	Desired percentage of cluster heads	d	Distance for data communication
r	Number of round	E_{elec}	Required energy for sending and receiving a single bit
G	Set of the nodes	$E_{TX_{elec}}(l)$	Energy dissipated in transmitting l bits
E_0	Initial energy of the nodes	$E_{RX_{elec}}(l)$	Energy dissipated in receiving l bits
E_{i_rs}	Residual energy of the ith node in EECRP	$E(i)$	Residual energy of ith node in HYREP
(X, Y)	Location of ith node in EECRP	$d(i)$	Distance from ith node to the sink
$(\overline{X_{ec}}, \overline{Y_{ec}})$	Energy centroid in EECRP	E_{max}	Maximum residual energy of the nodes
E_{fs}	Energy required by the amplifier in free space channels	d_{max}	Maximum distance between the nodes
E_{mp}	Energy required by the amplifier in multipath fading channels	α , β	Optimization coefficients in HYREP
d_0	Threshold distance in energy model		

1. INTRODUCTION

Recently, wireless sensor networks have attracted many researchers and engineers. These networks cover a wide range of applications from automation and smart transportation to healthcare issues. Therefore, these networks affect our lives in different ways [1, 2]. Smart cities use many WSNs for the city efficient operation. For instance, electrical distribution and automation systems are based on WSNs and Internet of Things (IoT) in large smart cities. Operation of WSNs is usually limited by the battery power. This issue becomes more important especially in harsh environments, such as dense jungles, in which the change of batteries is not easily

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accomplished [3]. Therefore, many researchers have worked on different methods in order to make battery-free WSNs. Therefore, the design of a low power WSN is vital for such applications. Many WSN designers work on low-power protocols and low power sensor nodes to reduce energy consumption. As an alternative, active research is on energy harvesters for battery-free WSNs. In fact, one of the popular methods for decreasing WSN dependency on batteries is using energy harvesters. These systems absorb environmental energies to produce power for battery charging. By using these systems lifetime of a network can increase significantly.

WSNs can be used in different environments such as jungles, malls, crowded cities, underwater, etc. [4]. For investigation of a network lifetime in each environment, a describing criterion must be defined. Three of the well-known criteria are First Node Dies (FND), Half Node Die (HND), and Last Node Dies (LND) [5]. FND is the elapsed time from the beginning of the network operation until the first node runs out of battery. HND means elapsed time until the death of 50% of the nodes in the network. LND means the time when the last node is dead. Considering the network situation would help to choose the most suitable criterion. For example, for a WSN, which is used in a hospital, the best lifetime criterion is FND, since the death of the first node may result in a loss of monitoring information of a patient. Consequently, failure may result in the death of a person. In some other situations such as bridge structure monitoring, the death of the first node means one small part of the bridge is not monitored and some data loss may happen, which is not critical. Thus, HND or LND would be suitable for evaluating the lifetime of the WSN monitoring a bridge condition [6].

WSNs are made for receiving and sending the data sensed by the sensors. Therefore, a large amount of energy is consumed on the communications. The rules of the communications are made by protocols. Consequently, designing a protocol that reduces the amount of energy for sending and receiving data, will help to improve the network lifetime. In other words, protocols play an important role in the amount of energy used for sending and receiving data packets.

In addition, it is an undeniable fact that adding energy harvesters to the sensor node can reduce the need for replacing batteries [7]. Therefore, a combination of an enhanced protocol with the use of energy harvesters on each sensor node is a novel idea, which can create hybrid networks with a long lifetime.

This paper is arranged as follows. Routing protocols are explained in section 2. In section 3, the communication model for investigation of energy consumption and cluster head selection are elucidated. In addition, the novel piezoelectric energy harvester is introduced in this section. The simulation results are discussed in section 4. Concluding remarks are at the end.

2. ROUTING PROTOCOLS

Every wireless sensor network is mainly made up of sensor nodes and a sink as a central node. In each network, a protocol is used for the management of sending and receiving the data from nodes. Therefore, in order to have a low power network, improvement of the protocol can be helpful. One of the methods for designing a low power WSN is the use of a suitable protocol [8]. Routing protocols are a category of protocols used in low power WSNs. These protocols are divided into three different types including flat, location-based and hierarchical [9]. In flat routing protocols, all the nodes have the same functionality and work together [10]. In fact, each sensor node has an identical role. These networks are only applicable to small networks. In location-based routing protocols, the information about the position of the nodes is found by special techniques such as Global Positioning System (GPS). Further decisions for calculations of the protocol will be based on the position of sensor nodes. Using the location information of nodes will help the network to meet the required expectations [11]. However, considering the location in the calculations cannot always be a sufficient solution to increase the network lifetime. The clustering protocols divide the network into clusters. There is a node in each cluster, which is called Cluster Head (CH). Each member node can be assigned to only one CH and sends the sensed data to its corresponding CH. CHs send the received data by means of a single path or multipath communication to the base station [12, 13].

The most famous traditional clustering protocol is called Low Energy Adaptive Clustering Hierarchy (LEACH) [14]. In the LEACH protocol, the CHs are chosen by random self-election. This protocol creates the clusters with a distributed algorithm, which nodes decide independently to become a CH without the help of a control center. The role of being CH rotates randomly among the nodes in order to balance the load of work and energy.

Operation of LEACH-based protocols has two phases in each round. In the first phase, a random value between 0 and 1, $pr(n)$, is calculated for each node n. If $pr(n)$ is less than a threshold value, node n turns into a CH. The threshold value in the main LEACH protocol is calculated by using Equation 1.

$$T(n) = \begin{cases} \frac{P}{1-P\times\left[r \bmod \left(\frac{1}{P}\right)\right]} & if\ n \in G \\ 0 & otherwise \end{cases} \quad (1)$$

where P is the desired percentage of CHs, r is the number of current round and G is the set of the nodes, which have not become CH in the last $1/P$ round.

In the second phase, the IDs of the defined CHs will be announced all over the network to make sure that all the nodes know the CHs. After this phase, non-CH nodes choose the closest CH as the assigned CH. Consequently, the clusters are made and the communications start in the second phase. After special elapsed time in the second phase, the network turns into the first phase again in order to choose the new CHs and re-cluster the network.

One of the famous routing protocols, which has been presented after the LEACH, is Power Efficient Gathering in Sensor Information Systems or PEGASIS. In this protocol, a chain is formed for all of the nodes to send the data to the sink [15]. Razaque et al. [16] presented a protocol, which is a combination of LEACH and PEGASIS. This protocol energy efficiency is better than LEACH and PEGASIS. Shortly after that, H-LEACH protocol is introduced for which the energy consumption is more reduced. This efficiency is due to considering the residual energy of the nodes and the maximum energy level in the network [17]. According to the analysis done in the references mentioned above, a properly efficient clustering protocol must consider four main factors including residual energy of the nodes, the position of the nodes, local independency, and network coverage. According to the investigations conducted by Shen et al. [18], none of the above protocols consider all four factors. However, a recent clustering protocol presented in 2017, takes all the factors into account. This protocol is called Energy Efficient Centroid-Based Routing Protocol (EECRP). This protocol superior performance over the older protocols is proved in literature [18].

EECRP operation is done in three different phases. In the first phase, which is the elementary evaluation, the sensor nodes send the sensed data to the sink. After this, the sink finds out about its distance to the nodes and divides the network into some clusters. The nodes also send the information about the residual energy. Therefore, the sink calculates the average residual energy of the network and the farthest distance. In the second phase, the first CH is chosen. In other words, the sink considers the nodes with maximum residual energy as a CH. Then the ID of the node, which must become CH is announced in the network. After reception of the IDs, the sensor nodes understand whether they are a CH or not and announce it in the network. In the third phase, which is called the return phase, the CH candidates for the next phase are selected. The selected node as CH in each cluster has more residual energy than the average residual energy of the cluster and its distance to the energy centroid of the cluster is less than the average distance of cluster members to the centroid.

In mathematics, the weigh centroid is a hypothetical point in which the mass is concentrated. In EECRP the energy centroid is used in order to optimize energy consumption. In fact, the energy centroid shows the distribution of the residual energy all over the network. The coordinates of the energy centroid are calculated in Equations (2) and (3).

$$\overline{X_{ec}} = \frac{\sum_{i=0}^{n} \frac{E_{i\_rs}}{E_0} . X}{N} \tag{2}$$

$$\overline{Y_{ec}} = \frac{\sum_{i=0}^{n} \frac{E_{i\_rs}}{E_0} . Y}{N} \tag{3}$$

where E_0 is the initial energy of the nodes, E_{i_rs} is the residual energy of the i^{th} node, n is the number of alive sensor nodes, N is the total number of the nodes, X , Y indicate the location of the i^{th} node and $\overline{X_{ec}}$, $\overline{Y_{ec}}$ are the results of the energy centroid.

In this paper, after the explanation of the proposed protocol, its superior performance over the LEACH and the EECRP is proved by the simulation results. The most significant feature of the proposed protocol is its optimized performance and compatibility with the energy harvester. The network operation after adding the energy harvester system to each node is presented in the simulation results.

3. THRESHOLD VALUE IN CUCKOO OPTIMIZED RELAY AND ENERGY-AWARE PROTOCOL

The threshold value can be defined according to several criteria. These criteria are dependent on the goals of the designed protocol. For example, if the goal is the enhancement of the Quality of Sent data (QoS), the criterion of communication noise will be used [4]. Also, for designing high-speed protocol, the delay criterion is considered [19].

The proposed protocol is a clustering, routing Hybrid optimized Relay and Energy-aware Protocol or simply HYREP. The goal of the HYREP protocol is enhancing the network lifetime. Therefore, the criteria for the definition of the threshold value are related to the energy consumption. The Cuckoo optimization algorithm is utilized to maximize energy efficiency. In addition, relay nodes in each cluster are considered for sending data to the CH. Thus, the energy consumption is minimized and the number of sent data packets is increased due to the more residual energies left in the sensor nodes. In order to analyze the energy consumption of the protocol, a suitable energy model should be used for the communication link. The communication model used for WSNs energy consumption is a first order communicational model that uses the distance from the transmitter to the receiver, one type of free space or multi-path fading channel [20].

Both the free space and multi-path fading channels are used according to the distance between the transmitter and receiver nodes. Free space (*fs*) model is used when the distance is less than a threshold value d_0, and the multipath (*mp*) model is considered when the distance is longer than d_0. The best value for d_0 has been calculated by Equation (4) according to literature [21].

$$d_0 = \sqrt{(E_{fs} / E_{mp})} \quad (4)$$

Energy values are calculated using Equations (5) and (6).

$$E_{TX}(l,d) = E_{TX_{elec}}(l) + E_{TX_{amp}}(l,d) = \begin{cases} l \times E_{elec} + l \times E_{fs} \times d^2, & if\ d \le d_0 \\ l \times E_{elec} + l \times E_{mp} \times d^4, & if\ d > d_0 \end{cases} \quad (5)$$

$$E_{RX}(l) = l \times E_{elec} \quad (6)$$

where E_{fs} and E_{mp} are the energy required by the amplifier in free space and multipath fading channels respectively. d is the distance and its unit is meter. l is the number of bits being sent or received. E_{elec} is the required energy for sending and receiving a single bit. E_{tx_elec} and E_{rx_elec} are the energy dissipated in transmitting and receiving l bits, respectively. This model is a standard model for simulating different protocols, so the results are comparable.

It is worth mentioning that each sensor node is made of several parts including a microprocessor, memory, battery, sensor, interface circuit and the radio part for sending and receiving data. The amplifier mentioned in the calculation of energies is a part of the radio circuit of the sensor nodes and the sink to send and receive the data.

3. 1. Threshold Value Equation

In the presented protocol, in each round a random number, *pr(i)*, is calculated for each node similar to the LEACH protocol. Then, for selecting a suitable CH for each cluster, Equation (7) is used instead of Equation (1) that was used in the LEACH.

$$T(i) = \begin{cases} P \times (\alpha \times \frac{d_{max}}{d(i)} + \beta \times \frac{E(i)}{E_{max}}) & if\, i \in G \\ 0 & otherwise \end{cases} \quad (7)$$

where G is the set of sensor nodes that haven't become CH in the last 1/P rounds, d_{max} is the maximum distance between the nodes and the sink, E_{max} is the maximum residual energy of the nodes, P is the desired percentage of CHs, $E(i)$ is the residual energy of the i^{th} node and $d(i)$ is the distance from node i to the sink. α and β are optimization coefficients, which normalize the threshold value according to $\alpha + \beta = 1$. In order to choose α and β, cuckoo optimization algorithm has been used.

As it was mentioned before, LEACH-based protocols have two phases. In the first phase, sensor nodes are not operating. Only the sink calculates the values and specifies the suitable nodes to become CH. The calculations are done considering Equation (7). Thus, nodes are not operating during these calculations and the residual energies are fixed.

According to the Equation (7), when the residual energy of the i^{th} node is high and the distance to the sink is low, $T(i)$ has a large value. Therefore, it is more probable that $pr(i)$ is less than $T(i)$. Consequently, since the condition for becoming a CH is that ($pr(i) < T(i)$), it is more likely that node i becomes a CH. As it is obvious in Equation (7), HYREP considers residual energies of the nodes and distances to the sink. These are the two most important factors considered for a protocol for efficient clustering. In addition, the decisions are made independently for each cluster. Therefore, HYREP has also the third factor: local independency. Finally, the ratio of the residual energy to the maximum amount of energy and the ratio of maximum distance to the sink are considered in the equation of threshold value. The ratio considerations result in the fourth factor of a proper clustering protocol: network coverage. Therefore, HYREP is comparable with EECRP. In addition, because HYREP takes the advantage of optimization algorithm as well as relay nodes in the communications, it consumes lower energy compared to EECRP and results in a longer network lifetime. This has been proved in the simulation results.

Another aspect of the HYREP threshold value is that it is dynamic and adapts its calculations to different networks. Indeed, d_{max} and E_{max} will be different in dissimilar networks. P as the desired percentage of CHs will also be different. Therefore, HYREP is not static, and its operation will adjust to different circumstances.

3. 2. Cuckoo Optimization Algorithm

In order to optimize network performance, several techniques can be combined together. For example, Hosseinirad [22] used the Genetic algorithm to achieve optimal cluster number and combined it with competition algorithms to find CHs.

There are several types of optimization algorithms, which are inspired by the nature, including Particle Swarm Optimization (PSO) with an inspiration of birds flocking [23–25], Ant Colony Optimization (ACO) inspired by the ants behavior of pheromone trail laying [25–27], and Genetic Algorithm (GA), which uses operators inspired by real variations of genetics [28]. Some of these algorithms are evolutionary. The advantages of evolutionary algorithms include robustness without the need of restarting in order to provide a solution in case of dynamic changes and a wide range of applications. It can solve all problems that can be formulated as optimization problems, and easily combine with other algorithms for more sophisticated problems.

Cuckoo Optimization Algorithm (COA) is one of the most useful evolutionary algorithms available today [29]. This algorithm considers the natural life of the cuckoo birds. Cuckoo birds, as one of the well-known parasitic category of birds, lay the eggs in other birds' nests. If the eggs are not recognized and killed by the host, they will grow and become a mature cuckoo. In each generation, the cuckoos become more mature and find a better environment to continue their parasitic life.

The main parameters considered in COA simulations are the number of iterations for repeating the algorithm until finding the solution, egg-laying radius, in which the cuckoos can fly, and limits of eggs that a cuckoo can lay.

This optimization technique has been applied to the proposed HYREP. The results of the optimization method are shown in the simulation section.

3. 3. Relay Node Usage Relay nodes have been employed in the HYREP to decrease the energy consumption of sending and receiving data packets. In the LEACH protocol, cluster members send and receive data directly to the CH, but in the HYREP, the path is different in some cases. After the CHs have been specified, the sink calculates the required energy for sending the data directly to the CH or through a relay node. Then it announces the result to the node. Therefore, nodes may send the data directly to the CH, or send the data to the relay node and then the relay node sends the data to the CH. Whichever method consumes less power will be used for data transmission. This technique can result in energy conservation and prevention of short lifetime. The two methods are shown in Figure 1.

As shown in Figure 1 (b), a relay node can provide a low power path to send data to the CH. Figure 2 shows the process of selecting a relay node for sending data to the CH in the HYREP protocol.

In the flowchart shown in Figure 2, m is the number of members in the cluster, in which the i^{th} node exists, E_{ic} is the required energy for transmission of data from i^{th} node to the cluster head C, E_{iR} is the energy needed for sending the data from i^{th} node to the relay node R, and E_{RC} is the required energy for the transmission of data from the relay node R to the cluster head C.

The sink node selects the relay node according to the cluster member node and CH positions. The sink also calculates the required energy for sending the data with and without using a relay node. Then, it sends a single command to the cluster member node, specifying whether it consumes less energy to send the data to the CH using the relay node or not. Therefore, the energy consumption of the sensor nodes does not increase when the relay node is included [30].

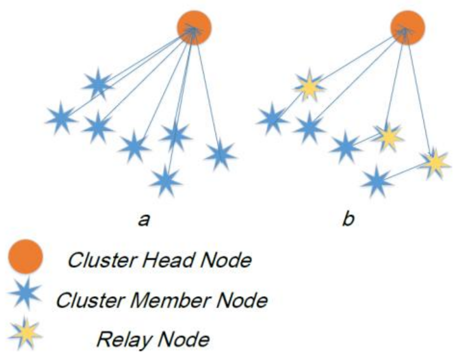

Figure 1. Using relay node, (a) shows data communication without considering the relay node, (b) illustrates data communication between a cluster member node and the CH with the help of relay nodes.

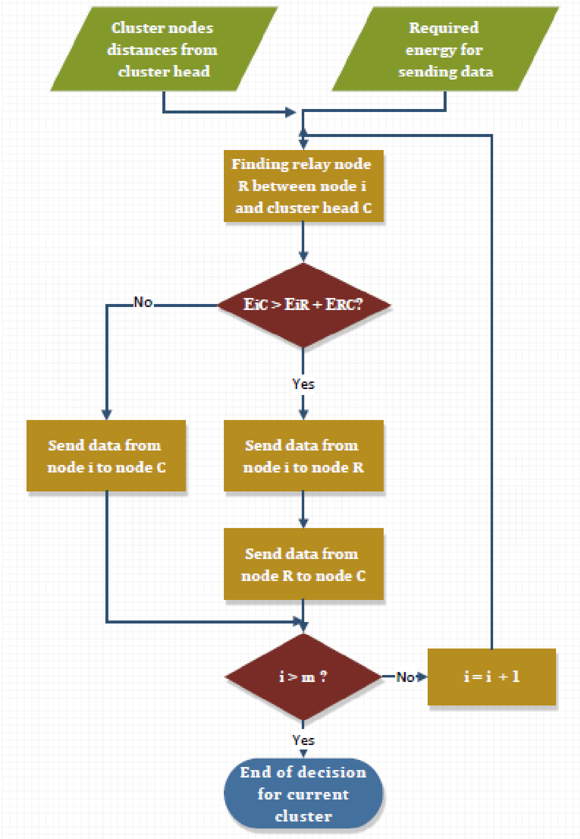

Figure 2. Path selection process in HYREP

3. 4. Piezoelectric Energy Harvester One of the hardware methods for increasing networks lifetime is the use of energy harvesters. Energy harvesters can play an important role in the design of long lifetime networks. These elements are capable of gathering environmental energies and converting the ambient energy to electrical energy. The converted electrical energy can supply the network as an extra battery source. Consequently, the frequency of battery replacement will be decreased.

One method of energy harvesting is using piezoelectric materials. Piezoelectric materials can convert physical pressure and vibration to electrical voltage and vice versa. The piezoelectric energy harvester can absorb environmental noise and vibration and convert it to electrical voltage. The energy harvester can be used in several environments such as a windy place, near a noisy road or in a factory. As a matter of fact, energy harvesters can provide a supplementary energy source to the WSN and increase the network lifetime [31]. An important characteristic of the energy harvester is the efficiency of conversion from ambient energy to the electrical energy.

In order to increase the conversion efficiency of the energy harvester used in this design, a special structure has been used. This structure is embedded in the sensor node and will function as an extra battery source. In this structure, the harvester is a cylindrical shape, on which four different beams stand, as shown in Figure 3. These beams are in triangular form since the triangular beams provide a larger output voltage when they vibrate [32]. Each of the designed piezoelectric beams has a special length. This length results in special resonance frequency. Therefore, the proposed piezoelectric energy harvester gather vibrational energy of four different resonance frequencies.

In fact to enable the harvester to gather low-frequency vibrational energy, the beams are made of 2 PZT layers and three Flame Retardant 4 (FR4) layers, as shown in Figure 4. PZT layers provide output voltage about 15 volts, a reasonable value for WSN nodes. FR4 layers are used in order to lower the operating frequency [33]. As a matter of fact, the FR4 material is a composite material. It is made of fiberglass and is used in printed circuit boards. This material helps to soften the movement of the beams and lower the resonance frequency. Therefore, the energy harvester beams are able to work in many environments and absorb energy within a wide range of vibrations. The resonance frequencies of the designed beams are less than 400Hz. Vibrations with frequencies below 400Hz are available in many different places, such as windy environments, airplane wings, forests, roads, etc.

The piezoelectric energy harvester has been simulated using COMSOL software and an extremely fine mesh has been chosen for very accurate results. As illustrated in Figure 5, the average output voltage is approximately 10~12.5 volts. In addition, according to the COMSOL simulation, the output current is around 80 micro Amperes. Consequently, a supplementary power source around 0.8~1 mW will be provided in each sensor node. This additional power source adds an extra 1mJ energy source in each round of network simulation. The energy efficiency and network lifetime calculations are illustrated in the next section. An important point to consider when adding the energy harvester to each sensor node is that it does not affect the operation of the algorithms of the protocol. It only results in higher residual energy of sensor nodes in each round. Therefore, the operation of the flowchart in Figure 2 stays the same as it was before adding the piezoelectric energy harvester.

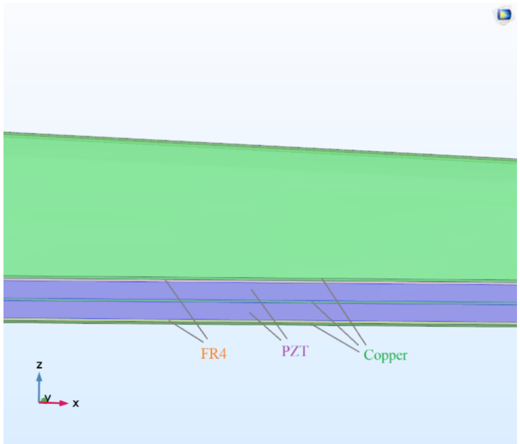

Figure 4. Beam Layers in piezoelectric energy harvester

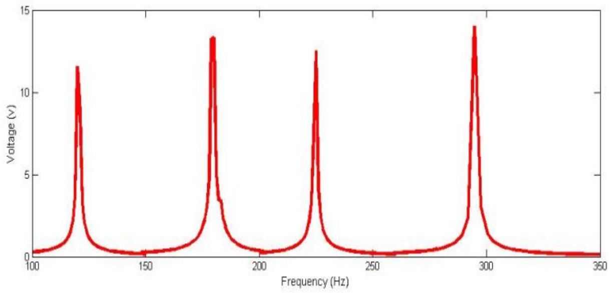

Figure 5. Output voltage of the piezoelectric energy harvester

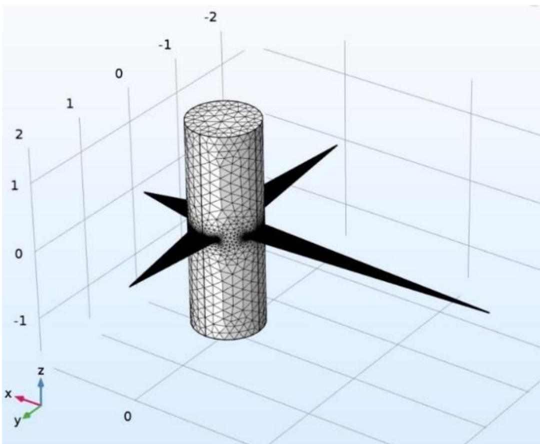

Figure 3. The piezoelectric energy harvester

4. SIMULATION RESULTS OF THE PROTOCOLS

For simulation of the proposed protocol, a wireless sensor network with 100 randomly located sensor nodes in a square field with the length of 100 meters is considered. According to Figure 6, the sink is located in the center of the network. The network parameters used in the simulations are listed in Table 1; Where E_{fs}, E_{mp} and E_{elec}, are the parameters used in the energy model for efficiency evaluation. As mentioned before, the energy model is obtained from literature [20].

HYREP energy efficiency is compared with that of the LEACH and the EECRP as shown in Figure 7. The energy harvesters are added to the network, which uses HYREP. According to Figure 7, the network that has the

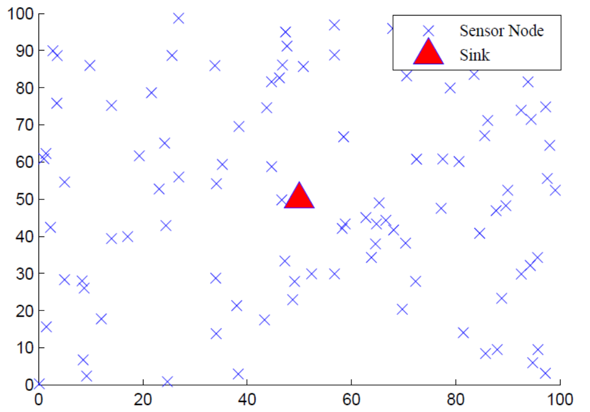

Figure 6. Network architecture

TABLE 1. Network Parameters

Network Parameter	Value
Initial energy of each node	1J
Data packet size	500bit
Controlling packet size	50bit
Efs	10pJ/bit/m2
Emp	0.0013pJ/bit/m4
Eelec	50 nJ/bit
d_0	87.7 m

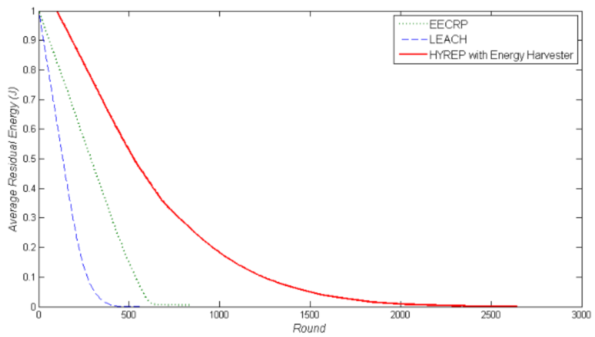

Figure 7. Residual Energy of the Nodes during Network Operation

piezoelectric energy harvester for each sensor node and uses HYREP protocol for its communication has the highest residual energy in all the simulation rounds. In other words, the residual energy of the nodes in a network using HYREP is saved during a longer simulation period, which means that the nodes consume less energy during the operation. It is also discernible that during the first rounds of network operation, the energy level with the help of the energy harvester stays at 1 Joule. After several rounds, the efficiency of the harvester starts to fall according to the environmental conditions. Therefore, the average energy of the nodes starts to fall under 1 Joule. The lower energy consumption of the nodes will result in a longer network lifetime. In order to evaluate this issue, the lifetime of three networks: the LEACH, the EECRP, and the HYREP with compatible energy harvester are compared. As mentioned before there are three primary types of lifetime including FND, HND, and LND. The extracted results of the lifetimes are shown in Figure 8. As illustrated in Figure 8, the lifetime of the network increases significantly by using the HYREP protocol and the compatible piezoelectric energy harvester for the nodes.

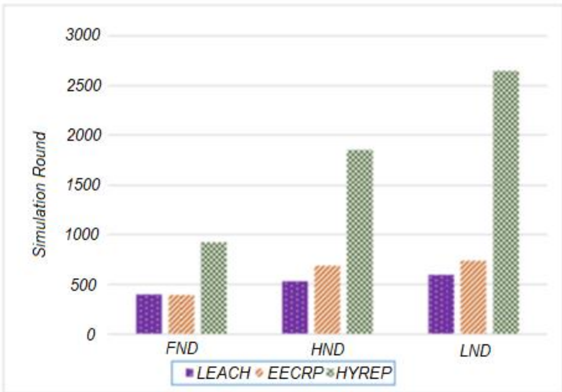

Figure 8. Lifetime of the network for 3 different protocols

5. CONCLUSION

In this paper, a new hybrid routing protocol is presented. The proposed protocol takes the advantage of a wisely chosen threshold value for finding the best CHs in the network. The protocol is also optimized by using Cuckoo Optimization Algorithm (COA). The HYREP uses relay nodes for sending data packets from CHs to the sink. This innovative protocol is also compatible with the specified energy harvester, which is introduced in this paper. The novel piezoelectric energy harvester is made of thin layers of PZT material as well as FR4 material to soften the vibrations. The presented harvester is embedded in each sensor node. According to the proper design of the HYREP protocol, the network lifetime is increased significantly in comparison to the traditional routing protocols such as LEACH and the modern protocol EECRP. For future improvement of this work, data compression can be considered for HYREP.

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HYREP: A Hybrid Low-Power Protocol for Wireless Sensor Networks

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چکیده

در این مقاله یک پروتکل مسیریابی هایبرید برای شبکه‌های حسگر بیسیم توان پایین ارائه شده است. سیستم جدید از یک دریافت‌کننده انرژی‌های محیطی برای افزایش طول عمر شبکه استفاده می‌کند. توان تلفاتی یکی از عوامل مهم در عملکرد طولانی مدت شبکه حسگر بیسیم می‌باشد. یک روش بهینه‌سازی برای انتخاب سرخوشه‌ها با استفاده از الگوریتم فاخته مورد استفاده قرار گرفته است. انرژی باقیمانده نقاط و فاصله تا مرکز برای محاسبه مقدار آستانه، علاوه بر نقاط رله برای این پروتکل استفاده شده است. روش هایبرید با استفاده از پروتکل بهینه‌سازی شده و دریافت‌کننده انرژی مجتمع باعث افزایش ۱۰۰ درصدی عمر شبکه نسبت به روش‌های دیگر اخیر می‌شود. شبیه‌سازی با استفاده از نرم‌افزار متلب نشان می‌دهد که مصرف انرژی به اندازه ٤٠ درصد کاهش یافته است.

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