

SEPCS: Prolonging Stability Period of Wireless Sensor Networks using Compressive Sensing

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Abstract: Compressive sensing (CS) is a developed theory that is based on the fact that a small number of linear projections of a sparse data contain enough information for reconstruction. In this paper, we propose a routing protocol called SEPCS for clustered Wireless Sensor Networks (WSNs) using CS. SEPCS combines a new clustering strategy with CS theory for prolonging stability period and network lifetime in WSNs. The simulation results demonstrate that SEPCS effectively prolong the stability period and the lifetime of the network compared to existing protocols.

Keywords: Cluster-based, Compressive sensing, Stability period, Network lifetime, Wireless sensor networks.

1. Introduction

The wide development in wireless communications have specifically given us the capability to produce small, low-cost sensor nodes that can wirelessly reach each other and compose a WSN. WSNs are made of a huge number of sensors deployed in a certain area. The sensors would transform physical data into a form that would make it easier for the user to understand. WSN technology is increasing quickly and becoming easier and cheaper to afford, granting different types of applications such as monitoring (seismic, health environments, etc.), control (tracking, object detection etc.), and surveillance (battlefield surveillance), topology and perimeter detection [1-6, 23-24]. WSNs are distinguished by higher unreliability, low power, computation and memory constraints and denser deployment of sensors. Therefore, the unique constraints and properties produce many challenges for the development and application of WSNs. Sensors are battery-powered and are expected to operate without attendance for a relatively long period of time. It is very difficult to recharge or replace batteries for the sensors. Due to the difference of WSNs from other wireless networks such as ad hoc networks, routing in WSNs is not easy task. All applications of WSNs have the requirement of transmitting the sensed data from multiple sensors to a specific destination called sink or Base Station. For this reason, resource management is required in sensors regarding storage, transmission power, processing capacity and on-board energy. In Routing, a careful management of resources is needed to increase the lifetime of the WSN. A number of routing protocols have been proposed for gathering data in WSNs due to such problems. The proposed routing technique considers the architecture and application requirements along with the properties of sensors. There are three main types of routing protocols: flat, hierarchical, and location based. In hierarchical protocols, where our new proposed protocol can be classified have special advantages related to scalability and efficient communication; they also provide energy-efficient routing in WSNs. In hierarchical the sensor nodes of WSN are grouped

into individual disjoint sets called clusters, each cluster has a selected node called cluster head (CH) and the remaining sensor are called cluster members (CMs). In WSNs, Clustering offers resource sharing, scalability, efficient use of constrained resources, communication overheads reduction and efficient resource allocation, i.e., clustering reduces the overall energy consumption and also decreases the interferences among sensor nodes. The basic idea of routing based clustering [7]–[9] is to use the information of the aggregated data at the CH to decrease the amount of transmitted data; i.e., decrease the dissipation energy in communication and consecutively gain the purpose of saving energy of the sensors. LEACH protocol in [10, 11], is the most popular routing protocol that uses cluster based routing in order to minimize the energy consumption. In LEACH, the job of the CH is to collect data from CMs and then transmits the summary to Base Station (BS). If CH is far away from BS, it requires more energy to transmit the summary to BS and therefore, it will die soon and for this reason LEACH has the lowest network lifetime. In [12], SEP is proposed as an improvement of LEACH. SEP is based on weighted election probabilities of each node to become CH according to the remaining energy in each node. SEP is heterogeneous-aware protocol, based on the effect of heterogeneity of sensors in terms of energy to prolong the stability period of WSNs. In SEP, some sensors have high energy with respect to others; therefore, the probability of these sensors to be CHs will be increased. SEP successfully increases the stable region than LEACH. In order to enhance the stability period of WSNs, the authors of [18] proposed WEP. WEP introduces a scheme to combine clustering strategy with chain routing algorithm to satisfy both energy and stable period constrains under heterogeneous environment in WSNs. However, in the proposed protocol, we discuss effectively the aggregation using CS and use the residual energy and the nodes concentration for CH selection. In addition, all the above protocols did not consider efficient data compression. In the proposed protocol, we develop an energy-efficient routing protocol in order to enhance the stability period of WSNs by combining CS and introducing new clustering technique. The proposed protocol provides accurate data recovery from a small number of compressed data. The simulation results show that the proposed protocol achieves a longer network lifetime and stability period compared with LEACH, SEP and WEP. CS is a recently revolutionary proposed mechanism [13] to gain a highly lower sampling rate for sparse data and accurate reconstruction using a few number of linear measurements.

It is a data compression technique to decrease the

communication cost without performing heavy computation or complicated transmission control. Using CS in WSNs optimizes energy consumption. This will result in prolonging network lifetime. Compressive sensing exploits the inherent correlation in some input data set X to compress such data by means of quasi-random matrices (uniformly distributed random numbers). If the compression matrix and the original data X have certain properties, X can be reconstructed from its compressed version Y , with high probability, by minimizing a distance metric over a solution space. In this paper, a new extended version of SEP is proposed, where we combine new clustering strategy with CS theory to satisfy both stability period and energy constraints in WSNs.

Sensor nodes arrange themselves into a set of clusters with selected one sensor as a CH according to the weighted election probabilities. Every CH compresses the received data from its CMs using CS and transmits it to the BS. Simulation results reveal that the proposed protocol greatly decrease the consumed energy and extend the stability period and network lifetime. Under CS framework, any data vector $X \in \mathbb{R}^N$ can be represented in the form,

$$X = \Psi S, \quad (2)$$

Here, $\Psi \in \mathbb{R}^{N \times N}$ the transform matrix and S is the sparse representation of X . The data X can be shown as a linear combination of K vectors with $K \ll N$ (then, K nonzero coefficients and $(N - K)$ zero coefficients in Equation 2). In many applications data has only a few large coefficients. These coefficients can be approximated by the K vectors. One would then select the K largest coefficients and discard $(N - K)$ smallest coefficients. Traditional compression techniques suffer from an important inherent inefficiency since they compute all N coefficients and records all zero coefficients, although $K \ll N$. Then, CS can replace traditional sampling and reduce the number of measurements. As a result, a small number of coefficients can be transmitted or stored rather than the full set of data coefficients. Consequently, CS provides a scheme that reduces power consumption, size and cost of the system. The measurements of X are $Y = \Phi X$, where $\Phi \in \mathbb{R}^{M \times N}$ is a sampling matrix with far fewer rows than columns ($M \ll N$). The measurements $Y \in \mathbb{R}^{M \times 1}$ are much easier than the original networked data $X \in \mathbb{R}^N$ to be stored, transmitted, and retrieved. Using Equation (2) the measurements can be expressed as,

$$Y = \Phi \Psi S, \quad (3)$$

If $A = \Phi \Psi$ satisfies the restricted isometry property (RIP) [13] condition $M \leq cK \log(N/K)$ such that c is a small constant with $c > 0$, the vector S can be accurately recovered from Y as the unique solution of

$$\hat{S} = \arg \min_S \|S\|_1 \quad s.t. \quad Y = \Phi \Psi S \quad (4)$$

The original networked data X may be sparse itself or can be sparsified with a suitable transform such as Discrete Cosine Transform (DCT) or Discrete Wavelet transform (DWT). One example of a self-sparse X is the linear combination of just K basis vectors, with $K \ll N$. that is; only K are nonzero and $(N - K)$ are zero [16]. Usually, the networked data X is sparse with a proper transform Ψ in Equation (2). In WSNs, sampling matrix Φ is usually pre-designed, i.e., each sensor locally draws M elements of the random projection vectors by using its network address as the seed of a pseudorandom number generator.

2. System Model

Most of the current hierarchical routing protocols provide enlarged network lifetime [19-23]. Spite, the main challenge in WSN is to extend the stability period. The longer the stability period is, the more information can be collected from the sensor field. To prolong the network stability, a new protocol (SEPCS) that merges routing, clustering with CS mechanism to fulfill energy and stability constrains is proposed. The new proposed protocol maximizes the lifetime of WSN by aggregating data using CS and a new technique to select the CHs using residual energy and node concentration is proposed.

2.1 Network and energy model assumptions

The energy model in [11] and represented in Fig. 1 is used in SEPCS. According to this model, the energy consumed to transmit L -bit message over a distance d , is calculated as follows:

$$E_{Tx}(L, d) = \begin{cases} L \cdot E_{elec} + L \cdot \epsilon_{fs} \cdot d^2 & \text{if } d \leq d_0 \\ L \cdot E_{elec} + L \cdot \epsilon_{mp} \cdot d^4 & \text{if } d > d_0 \end{cases} \quad (5)$$

Here, E_{elec} is the energy consumed per bit to execute the transmitter or the receiver circuit, ϵ_{fs} and ϵ_{mp} depends on the transmitter amplifier model. By equating the two expressions at $d = d_0$, we have $d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}}$. To receive an L -bit message the radio expends $E_{Rx} = L \cdot E_{elec}$.

The presumption of our protocol are as follows:

- N sensors are uniformly deployed within field of area $R \times R \text{ m}^2$,
- All sensors and BS are static.
- Communication is based on multi-hop scenario.

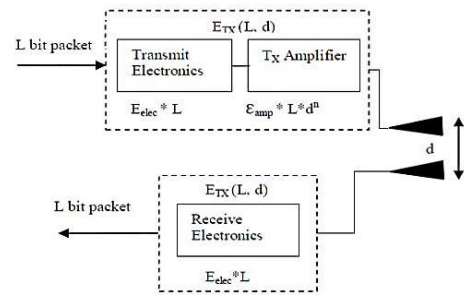


Figure 1. The energy consumption model.

2.2 Optimal number of clusters

For simplicity, we assume that BS is located at field center and the distance between any node to the BS or its CH is less than or equal to d_0 . Then, the energy consumed by CHs during one round is computed as:

$$E_{CH} = \left(\frac{N}{C} - 1\right) Y E_{elec} + \frac{N}{C} Y + Y E_{elec} + Y \epsilon_{fs} d_{BS}^2, \quad (6)$$

Here, clusters number is C , compressed data is Y and d_{BS} is the average distance between CH and BS. The energy consumed by CMs is computed as:

$$E_{nonCH} = L \cdot E_{elec} + L \cdot \epsilon_{fs} d_{CH}^2, \quad (7)$$

Here, d_{CH} is the average distance between CMs and their CH. the occupied area by each cluster can be computed using Euclidian distance as $A = \frac{R^2}{2\pi C}$ with node distribution $\rho(x, y)$:

$$\begin{aligned} d_{CH}^2 &= \iint (x^2 + y^2) \rho(x, y) dx dy \\ &= \iint r^2 \rho(r, \theta) r dr d\theta, \end{aligned} \quad (8)$$

We assume that the area is a circle with radius $\eta = R/\sqrt{\pi C}$, $\rho(r, \theta)$ is constant and the density ρ is uniform where $\rho = (1/(R^2/C))$, d_{CH}^2 can be simplified as follows:

$$\begin{aligned} d_{CH}^2 &= \iint \int (x^2 + y^2) \rho(x, y) dx dy \\ &= \rho \int_{\theta=0}^{2\pi} \int_{r=0}^{R/\sqrt{\pi C}} r^3 dr d\theta = \frac{R^2}{2\pi C}, \end{aligned} \quad (9)$$

In each round, the energy consumed by every cluster is computed as:

$$E_{cluster} \approx E_{CH} + \frac{N}{C} E_{nonCH}, \quad (10)$$

In each round, the total energy consumed by all sensor nodes is:

$$E_{tot} = C E_{cluster} = Y(N(1 + E_{elec}) + C \epsilon_{fs} d_{BS}^2) + NL(E_{elec} + \epsilon_{fs} d_{CH}^2), \quad (11)$$

Differentiating E_{tot} with respect to C and equating to zero, the optimal number of clusters is computed as follows:

$$C_{opt} = \sqrt{\frac{NL}{2\pi Y} \frac{R}{d_{BS}}} = \sqrt{\frac{NL}{2\pi Y} \frac{2}{0.765}}, \quad (12)$$

d_{BS} is the average distance between CH to BS is:

$$d_{BS} = \int \sqrt{x^2 + y^2} \frac{1}{A} dA = 0.765 \frac{R}{2}, \quad (13)$$

If the distance of a large number of nodes to the BS is bigger than d_0 then, follow same analysis as in [5]:

$$C_{opt} = \sqrt{\frac{NL}{2\pi Y} \frac{\epsilon_{fs}}{\epsilon_{mp}} \frac{R}{d_{BS}^2}}, \quad (14)$$

The optimal probability of a node to become a CH, p_{opt} , can be computed as follows:

$$p_{opt} = \frac{C_{opt}}{N}, \quad (15)$$

The optimal number of clusters is very important issue.

The work in [10] cleared that the energy consumed in the network per round will be exponentially increased if the optimal number of clusters are not found, either when the number of clusters is more than the optimal number of clusters; where the total routing traffics within each cluster will be reduced because of fewer members; however, more clusters will result in multi-hop transmissions from CHs to BS and every CH will receive data from fewer members this will decrease the local data aggregation and increase the communications among the CHs, or when the number of clusters is less than the optimal number of clusters; where some nodes in the network have to send their sensed data far to reach CH, causing the global energy in the system to be large.

2.3 Cluster head election phase

Finding the optimal number of clusters implies the optimal selection of a node to be a CH. The cluster is optimal if the energy consumption is well distributed among all sensors and the total energy consumption is minimized. Since energy consumption of the CHs is approximately high, so the residual energy of sensor is the main criteria for CH selection. In addition, data aggregation can save considerable energy when

the source nodes constructing a cluster when these nodes in a nearly small region while the BS is far away from the source nodes, because sensors require much less energy for transmitting data to the CH than transmitting it directly to the BS when the BS is located at a remote distance. Therefore, it is reasonable to derive that the closer source nodes within a cluster, the lower energy they need to consume to transmit data.

According to the discussion above, the selection of CHs in SPCS will be based on concentration degree and residual energy of sensor nodes.

Definition 1: Given WSN of N the concentration degree of a node i , $D^r(i)$ ($i = 1, 2, \dots, N$) is the number of sensor nodes that can sense during the r^{th} round.

Definition 2: Election weight of node i in round r $W(i, r)$ is defined as:

$$W(i, r) = \alpha \frac{E_i^r}{\bar{E}^r} + (1 - \alpha) \frac{D^r(i)}{p_{opt}}, \quad (16)$$

Here, $\alpha = \frac{1}{1+\beta}$ is an adaptive factor to regulate the effect of residual energy and concentration degree on the election weight, $\beta = \frac{E_i^r}{\bar{E}^r}$ denotes the average residual energy of node i in round r , E_i is the initial energy of node i and \bar{E}^r is the average residual energy of network in r^{th} round. With the reduction of residual energy, α will gradually increase to adapt to decrease the number of effective sensors in WSN.

2.4 Setup phase

- Step 1: During the initialization, every sensor computes its concentration degree and ticks its level as level 1.
- Step 2: Initialization phase: In "CH selection" messages, \bar{E}^r will be broadcasted by BS. Every node i compares its E_i^r with \bar{E}^r . If $E_i^r \geq \bar{E}^r$, i computes its $D^r(i)$ and E_i^r , and sends the weight with its ID to the BS for CH selection in "CH selection" message. Otherwise, a node i abandons CH selection, and selects to join a CH later.
- Step 3 BS ticks its level as level 1, selects C_{opt} sensors that have maximum selection weight as CHs. Every selected CHs broadcasts to report its neighbors that it has been selected as a CH.
- Step 4 If a sensor is selected as a CH, it will broadcast "re-join" messages to each non-CH sensor. After receiving the broadcast message, every non-CH selects its nearest CH according to the received signal strength and then notifies the CH by transmitting a join message.
- Step 5 CH sets up TDMA schedule and sends it to its CMs.

2.5 Data transmission phase

After forming the clusters and receiving the TDMA schedule, the transmission phase of the data can start. The sensors periodically gather the data samples $X = [x_1, \dots, x_N]$, and send it during their allocated transmission time to the CH.

$$X = DS, \quad (17)$$

Here, $S \in \mathbb{R}^N$ is the transform coefficient vector which contains K ($K \ll N$) nonzeros, and D is the DWT basis. After receiving all data, CHs compress the gathered data using CS. The received data vector at CH can be rewritten as:

$$Y = \Phi X = \Phi \Psi S, \quad (18)$$

Here, Φ is the sampling matrix whose entries are i.i.d Gaussian with zero mean and unit variance. Subsequently CHs transmit measurements Y to the BS independently. Finally, the BS decodes the networked data X from Y .

3. Simulation Results

In this section, using Matlab and Sparselab toolbox [17], we prove the efficiency of the proposed protocol and compare the results with the baseline algorithms in terms of energy consumption and network lifetime and the stability period. The parameters of the simulation are listed in table. I.

Table 1. Simulation parameters.

Description	Parameter	Value
No. of nodes	N	1000
Initial energy	E_0	0.5
Location of the BS	BS	(50,50)
Data packet size	L	4000 bits
Network area	$R \times R$	$200 \times 200 m^2$
Transmit amplifier if $d_{BS} \leq d_0$	ϵ_{fs}	$10 pJ/(bit * m^2)$
Transmit amplifier if $d_{BS} \geq d_0$	ϵ_{mp}	$0.0013 pJ/(bit * m^4)$
Threshold distance	d_0	87.7058 m
No. of nonzero Coefficients	K	10
No. of measurements	M	50
Propagation loss factor	γ	2

We choose the number of nonzero coefficients $K = 10$ such that $K < M \ll N$. Fig. 2(a) shows Network topology comprised of 100 sensor nodes corresponds to DWT basis. The networked data shown in Fig. 2(b) can be presented with $K = 10$ nonzero coefficients after DWT transform.

3.1 Performance metrics

In our simulation, we used the following metrics to validate the performance of the proposed protocol SEPCS:

- Network lifetime: is the time interval from the start of operation of WSN until the death of all sensor nodes.
- Throughput: is the rate of data sent from CHs to BS over the lifetime of the network.
- Stability period: is the time interval from the start of network operation until the death of the first alive node.

Algorithm 1 Stable Election Protocol using CS

Input Parameters: Table 1 listing the input parameters of this algorithm

For each round

BS broadcasts the average residual energy of network

For each node

Node calculates its concentration degree as in Def. 1

If (residual energy of node \geq average residual energy of WSN)

Node computes its election weight as Equation (16)

BS chooses CHs with maximum election weight

Set coordinates x and y

Set energy amount,

Set used node

Increment CH count

End if

If (node i is CH)

If (distance between node j and CH $\leq d_0$)

Transmission cost is

$$E_{Tx}(l, d) = L \cdot E_{elec} + L \cdot \epsilon_{fs} \cdot d^2$$

Subtract the Transmission cost from j

End if

If (distance between node j and CH $> d_0$)

Transmission cost is $E_{Tx}(l, d) = L \cdot E_{elec} +$

$$L \cdot \epsilon_{mp} \cdot d^4$$

Subtract the transmission cost from j

End if

CH compresses data according to Equation (18)

Reception cost is $E_{Rx} = Y \cdot E_{elec}$

If (remaining energy ≤ 0)

Display node has died

End if

Subtract the reception cost from i

If (remaining energy ≤ 0)

Node has died

End if

CH sends its measurements to BS

End if

BS decodes S from measurements Y as Equation (4)

End for

End for

Output: $\hat{X} = \widehat{DS}$

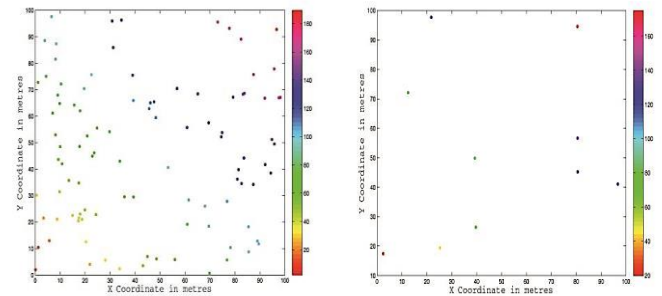


Figure 2. Sparsity of networked data in a DWT basis.

3.2 Energy consumption

Energy consumption is the main issue in WSNs, in the first test, we discuss the effect of using CS on energy consumption. We compare the achievement of SPECS with baseline WEP, SEP, and LEACH protocols. Fig. 3 shows the energy consumption per round in SPECS, WEP, SEP and LEACH protocols. It shows that WEP earns superior achievement in comparison with SEP, whereas WEP considers chain among CHs instead of all nodes, to reduce the energy dissipated in each round. Also, SEP performs better than LEACH because the advanced sensors die more slowly than normal sensors in SEP. It is obvious that the energy consumed of SPECS is much lower than that of WEP, SEP and LEACH because SEPCS utilizes data compression using CS and select the CHs utilizing the computed election weight which is based on residual energy and the concentration degree of sensors. Therefore, the total network energy consumption is minimized compared with WEP, SEP and LEACH.

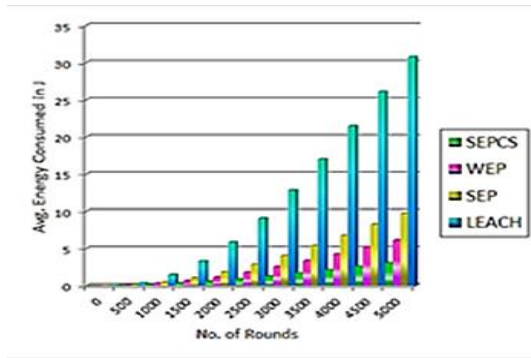


Figure 3. Average energy consumption.

3.3 Network lifetime

In WSNs, total survival network lifetime is considered as one of the most important metric. In the second test, the network lifetime of SEPCS is computed and compared with existing protocols. Fig. 4 shows the network lifetime of LEACH, SEP, WEP and SEPCS. It shows the number of alive nodes with respect to number of rounds. From the figure, both the death time of first node and the death time of last node of SEPCS takes place later than those of LEACH, SEP and WEP. Also, WEP performs better than SEP because WEP uses chain among CHs instead of all nodes in order to alleviate the excessive delay to transmit data to BS. As well, SEP performs better than LEACH, the reason is every sensor node independently elects itself as a CH based on its initial energy relative to that of other nodes. However, the network will be alive for a longer period of time with our proposed protocol compared with LEACH and SEP because SEPCS efficiently compresses data using CS, consequent to this compression; the total network energy consumption is minimized. In addition, SEPCS uses residual energy and degree concentration of sensors to select CHs. where sensors with high election weight has greater chances to be a CH..

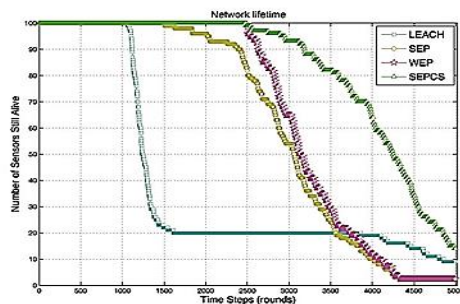


Figure 4. Number of alive nodes over rounds.

3.4 Throughput

In the third test, the overall throughput is evaluated in terms of number of received messages exchanged at BS using LEACH, SEP, WEP and SEPCS. Fig. 5 shows that the overall throughput of SEPCS is significantly greater than those of LEACH, SEP and WEP protocols because SEPCS efficiently compresses data using CS and optimizes energy usage to reduce storage space and energy consumed, and also the CHs selection mechanism is based on the residual energy and the concentration degree of sensors.

Also, it shows that the throughput of WEP is better than SEP because WEP uses greedy algorithm to make a chain among the selected CHs for achieving more throughput gain. As well

as the throughput of SEP is significantly larger than that of LEACH because SEP guarantees CHs in more rounds.

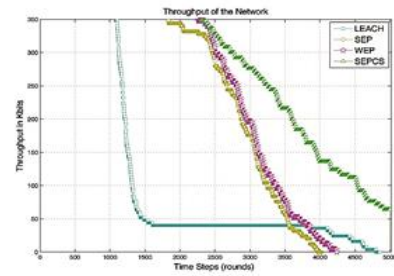


Figure 5. Throughput of the network.

3.5 Stability

In WSNs, the stability period is crucial for many applications where the feedback from the sensors must be reliable. In the fourth test, we study the sensitivity of SEPCS protocol and compare the results with other protocols in terms of the stability period length of LEACH, SEP, WEP and SEPCS. It shows that SEPCS outperforms WEP by up to 19.6%, SEP by up to 23.4% and LEACH by up to 39.1%, i.e., the proposed SEPCS is significantly prolongs the stability period compared to LEACH, SEP and WEP. This is because SEPCS efficiently compresses data to a great ratio and the selection of CHs is carried in an optimal way, therefore, stability period of SEPCS is enhanced which is the main requirement for the lifetime of the WSN.

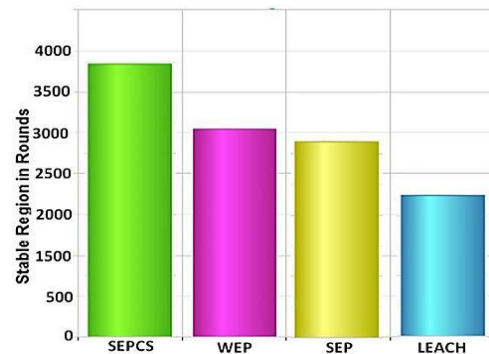


Figure 6. Network stable period.

Table 1. Average percentage of energy consumption, lifetime, throughput and stability in leach, SEP, WEP and SEPCS.

Protocols	Avg. Energy consumption	Avg. Lifetime	Avg. Throughput	Avg. Stability
LEACH	58.3%	38.4%	32.5%	43.0%
SEP	18.5%	61.7%	52.2%	58.7%
WEP	11.6%	63.8%	60.6%	62.5%
SEPCS	5.8%	81.6%	74.7%	82.1%

4. Conclusion

In this paper, we propose a compressive sensing enhancement for the SEP to increase the stability period, load balancing, lifetime of WSN. CS measurements are obtained via cluster heads. Discrete Wavelet Transform is utilized as the sparsifying matrix and independent and identically distributed Gaussian with zero mean and unit variance is used as the sampling matrix. The CH selection is based on residual energy and concentration of sensors. The simulation results show that the proposed protocol reduces the energy consumed and so it

extends the stability period and the lifetime of the network compared to LEACH, SEP and WEP.

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