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PEAL: Power Efficient and Adaptive Latency Hierarchical Routing Protocol for Cluster-Based WSN

Faouzi Hidoussi[1] · **Homero Toral-Cruz**[2] · **Djallel Eddine Boubiche**[3] · **Rafael Martínez-Peláez**[4] · **Pablo Velarde-Alvarado**[5] · **Romeli Barbosa**[2] · **Freddy Chan**[2]

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Abstract In wireless sensor networks, one of the most important constraints is the low power consumption requirement. For that reason, several hierarchical or cluster-based routing methods have been proposed to provide an efficient way to save energy during communication. However, their main challenge is to have efficient mechanisms to achieve the trade-off between increasing the network lifetime and accomplishing acceptable transmission latency. In this paper, we propose a novel protocol for cluster-based wireless sensor networks called PEAL (Power Efficient and Adaptive Latency). Our simulation results show that PEAL can extend the network lifetime about 47% compared to the classic protocol LEACH (Low-Energy Adaptive Clustering Hierarchy) and introduces an acceptable transmission latency compared to the energy conservation gain.

Keywords Wireless sensor networks · Cluster-based routing protocols · Distance · Energy-efficient · Latency · Inter-cluster transmission

1 Introduction

Wireless sensor networks (WSN) have been recognized as one of the emerging technologies of the twenty-first century [1, 2]. WSN consist of several sensor nodes that collect data in inaccessible areas and send them to the base station (BS) after initial processing [3]. At the same time, sensor networks have some special characteristics compared to

✉ Homero Toral-Cruz
htoral@uqroo.edu.mx; homerotoralcruz@gmail.com

1 Corgascience Limited, Doha, Qatar

2 Department of Sciences and Engineering, University of Quintana Roo, Chetumal, Mexico

3 LaSTIC Laboratory, Department of Computer Science, University of Batna 2, Batna, Algeria

4 Facultad de Tecnologías de Información, Universidad de la Salle Bajío, León, Mexico

5 Area of Basic Sciences and Engineering, Autonomous University of Nayarit, Tepic, Mexico

traditional networks which make it hard to deal with this kind of networks. The most important property that affects these types of networks is the limitation of the available resources, especially the energy [4]. Sensor nodes carry limited, generally irreplaceable, power sources. Therefore, they must have inbuilt trade-off mechanisms that give the end user the option of prolonging the network lifetime at the cost of lower throughput or higher transmission latency [3]. Routing techniques are the most important issues for such kind of networks where resources are limited. Cluster-based protocols have been proposed to provide an efficient way to save energy during communication such as LEACH [5], TEEN (Threshold sensitive Energy Efficient sensor Network) [6], PEGASIS (Power-Efficient GAthering in Sensor Information Systems) [7] and HEEP (Hybrid Energy Efficiency Protocol) [8]. In these protocols, nodes are organized into clusters where cluster heads (CHs) pass messages, between their member nodes and the base station.

Multipath routing methods are often used in WSN to reduce frequent routing update, enhance data transmission rates and provide an even distribution of traffic load over the network. The main idea of these methods is to achieve a balance in the energy consumption for extending the network lifetime. However, multipath routing increases the latency, which generates a new problem, in scenarios where applications require fast responses [9, 10].

In order to contribute to achieve the trade-off between the energy consumption and the transmission latency in a multipath routing, we propose the PEAL protocol. PEAL protocol takes into account the conservation of energy and the minimization of latency. The rest of the paper is organized as follows: Sect. 2 presents related works. Then, radio energy dissipation model is described in Sect. 3. The proposed protocol is detailed in Sect. 4. In Sect. 5, we present simulation results obtained from our proposal. Finally, Sect. 6 concludes the paper highlighting the achievements from this work.

2 Related Works

During the last few years, a lot of clustering algorithms have been proposed for wireless sensor networks. Grouping a large number of sensors into clusters and keeping them communicating regularly are quite complex. Here, we mention some of the most recent works in different views of clustering.

In [11], Heinzelman et al. developed and analyzed LEACH, an application specific protocol architecture for microsensor networks. LEACH divides time into rounds. Clusters are organized at the beginning of each round and data are transferred from the nodes to the cluster head and on to the base station after the set-up phase. As LEACH is a typical clustering protocol, several modifications have been made PEGASIS [7], LEACH-E [12], LEACH-D [13], Mod-LEACH [14], LEACH-E (ELE) [15] and HEEP [16].

In [7], Lindsey et al. proposed PEGASIS. PEGASIS creates a communication chain using a TSP (Traveling Sales Person) heuristic. Each node communicates only with its two closest neighbors along the communication chain. Only a single designated node gathers data from the other nodes and transmits the aggregated data to the sink node.

The distance factor is not considered in LEACH algorithm [11], for this LEACH-D was proposed in [13]. In the setup phase, author in [13] introduce a new threshold $T(S)_{new}$, related to the node's distance from the *BS*. LEACH-D [13] is a distributed cluster heads competitive algorithm, where cluster head selection is primarily based on the distance of each node from BS. Next, each node becomes a cluster head with the same probability threshold which is predefined. Other nodes keep sleeping until the cluster head selection stage ends. Generally more clusters should be produced closer to the base station. That is to say, the node's probability threshold should decrease as its distance from the base station decreases. The distance factor is introduced as follows:

$$distance = 1 - c\frac{d(s_i, BS) - d_{min}}{d_{max} - d_{min}}, \tag{1}$$

where d_{max} and d_{min} denote the maximum and minimum distance between sensor nodes and the base station, $d(s_i, BS)$ is the distance between node s_i and the base station B, c is a constant coefficient between 0 and 1 [13].

Therefore, $T(S)_{new}$ is multiplied with a factor representing the distance from BS to a node:

$$T(S)_{\text{new}} = \begin{cases} \dfrac{p}{1 - p * \left(r \bmod \dfrac{1}{p}\right)} * distance, & \text{if } S \in G \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

The election probability, p of nodes $S \in G$ to become cluster heads increases in each round in the same epoch and becomes equal to one in the last round of the epoch. Note that we define a time interval by round where all cluster members have to transmit to the cluster head.

After the cluster heads are selected, adding nodes to an appropriate cluster head is the key problem, which is important for balancing energy consumption in the area of the cluster head [13]. In order to solve this problem, Shang introduces a new function in [13]. According to this function, each node can decide which cluster head to prolong them. Hence, this functions based on remaining energy and distance.

When the network diameter is increased beyond certain level, the distance between the cluster-head and the base station is increased enormously. This scenario is not suitable for LEACH [11] routing protocol in which the base station is at single-hop to cluster-head. In this case energy dissipation of cluster-head is not affordable. To address this problem, Multi-hop LEACH is proposed in [17].

Like LEACH [11], in Multi-Hop LEACH [17] some nodes elect themselves as cluster-heads and other nodes associate themselves with elected cluster-head to complete cluster formation in the setup phase. In the steady state phase, the cluster-head collects data from all the nodes in its cluster and transmits data directly or through other cluster-head to the Base station after the aggregation. Multi-Hop LEACH allows two types of communication operations; inter-cluster communication and intra-cluster communication. In Multi-hop inter-cluster communication, the whole network is divided into multiple clusters each cluster has one cluster-head. This cluster-head is responsible of the communication for all the nodes in the cluster. The cluster-head receives data from all the nodes at single-hop and aggregates and transmits directly to the sink or through intermediate cluster-head. In Multi-hop inter-cluster communication when distance between cluster-head and base station is larger the cluster head uses intermediate cluster-head to communicate with the base station.

Figure 1 describes Multi-Hop LEACH communication architecture. Randomized rotation of cluster-head is similar to LEACH. Multi-Hop LEACH selects best path with minimum hop-count between first cluster-head and the base station.

HEEP [16] protocol combines two algorithms, LEACH and PEGASIS. HEEP suggest a new network self-organization approach, that joins clusters-based and the chain-based

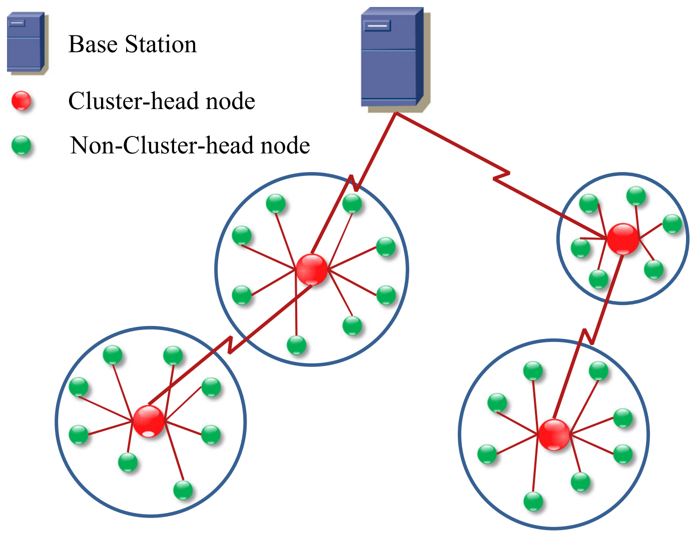

Fig. 1 Multi-hop LEACH

approaches. This new approach is called chains clustering approach. Organizing the network nodes into chains clusters avoids the bad energy dissipation in LEACH protocol and reduces the routing latency generated by PEGASIS protocol. Based on the chains clustering approach, in each cluster adjacent chains nodes are formed and the most powerful node is selected to be the cluster head. All the nodes will transmit their collected data to their CH using neighboring chains of nodes. Then CHs transmit the received data directly to the base station, or indirectly through the neighboring CHs, as shown in Fig. 2. Transmitting collected data through the neighboring chains nodes can reduce the transmission distances and optimize the energy consumption. Data aggregation is applied by each node in a chain, to reduce the amount of exchanged data between nodes and their CH, which preserves energy reserves.

3 Radio Energy Dissipation Model

We assumed a simple model that was proposed in [11] for the radio hardware energy dissipation where the transmitter dissipates energy to run the radio electronics and the power amplifier, and the receiver dissipates energy to run the radio electronics as shown in Fig. 3.

Using this radio model, to transmit $k-$bit of message at distance "d" the radio expends:

$$\begin{aligned} E_{Tx}(k,d) &= E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \\ E_{Tx}(k,d) &= E_{elec} * k + \varepsilon_{amp} * k * d^2. \end{aligned} \tag{3}$$

And to receive this message, the radio expends:

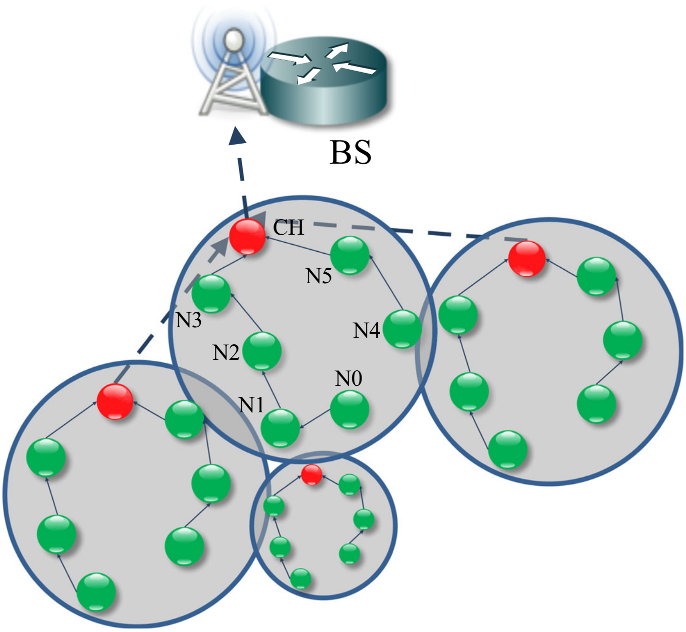

Fig. 2 Chained clusters organization

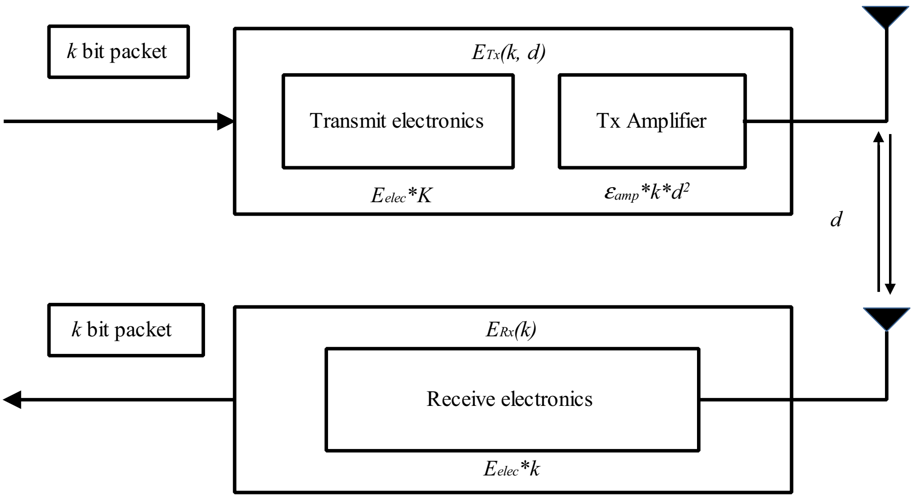

Fig. 3 Radio energy dissipation model [11]

$$\begin{aligned} E_{Rx}(k) &= E_{Rx-elec}(k) \\ E_{Rx}(k) &= E_{elec} * k. \end{aligned} \tag{4}$$

4 The Proposed Protocol

In this section, we propose a novel routing protocol for wireless sensor networks. The proposed protocol is named Power Efficient and Adaptive Latency. Routing in PEAL works in rounds and each round is divided into two phases, the setup phase and the steady state phase. Each sensor knows when each round starts using a synchronized clock [11]. The next subsections explain the setup and the steady state phases.

4.1 Initial Assumptions

This paper considers a WSN deployed for critical applications (application that tolerates with the normal latency and does not tolerate with high latency). The following assumptions are made about the sensor nodes and the network model:

- The base station (i.e. sink node) is located outside the sensing field.
- Nodes are location-aware, i.e. equipped with GPS capable antennae.
- The communication channel is symmetric.
- Gathered Data can be aggregated into single packet by the cluster heads.
- Nodes are left unattended after deployment. Therefore, battery re-charge is not possible.

4.2 Setup Phase

In this phase, each sensor checks its ability to become a CH based on the following key points: desired percentage of CHs, current round, the distance between sensor nodes and their nearest base station and remaining energy. At the beginning of each round, CHs elect themselves. In order to determine the eligibility of the sensor to be a CH, each sensor S generates a random number which is between 0 and 1; then this number is compared to a sensor variable threshold value $T(S)$; if the value of the threshold is greater than the random number, the sensor becomes a CH for the current round R. The Threshold can be calculated using the formula proposed in [11];

$$T(S) = \begin{cases} \dfrac{p}{1 - p * \left(r \bmod \dfrac{1}{\mathrm{p}} \right)} & \text{if S} \in \text{G} \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

In fact, the remaining energy and distance are not considered in LEACH protocol. As a result, the election of a CH with low energy and which is located far from the SB can affect the network lifetime. In order to increase the network lifetime, our proposal considered the remaining energy and the distance to elect the best sensor node as a CH. The remaining energy (RE) factor is calculated as follows:

$$RE = \left\{ \frac{E_{current}}{E_{max}} \right\}, \tag{6}$$

where $E_{current}$ is the current energy of node and E_{max} is the initial energy of node. Hence, the new formula to compute the threshold value is:

$$T(S)_{\mathrm{PEAL}} = \begin{cases} \dfrac{p}{1 - p * \left(r \bmod \dfrac{1}{p} \right)} * distance * RE & \text{if } S \in G \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

where, the *distance* factor is calculated by Eq. (1).

4.2.1 Advertisement

After CHs have been selected, they broadcast advertisement messages to the rest of the sensor nodes in the network. For these advertisement messages, CHs use a carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol. All CHs use the same energy when transmitting advertisement messages. In this phase, non- CHs nodes must be awake in order to receive the advertisement messages from the CHs.

4.2.2 Decision

After non-cluster head nodes have received advertisement messages from one or more CHs, the sensor nodes compare the received signal strength[1] from received advertisement messages. Then, they decide to which cluster they will belong.

Adding nodes to an appropriate CH is the key problem, which is important for balancing energy consumption in the area of CH [11]. To add a new node to an appropriate CH the proposed protocol uses the same function described in [13]. This function is based on remaining energy and distance:

$$f(i,j) = \frac{c(n_i, CH_j)}{E_{CH_J}}. \tag{8}$$

The condition for adding node i to CH_j is to make the cost function $f(i,j)$ minimal, where E_{CH_J} denotes current energy of $j-$ th cluster head and:

$$c(n_i, CH_j) = \frac{d^2(n_i, CH_j)}{d^2_{n-CH}}, \tag{9}$$

where $d^2(n_i, CH_j)$ denote the distance from $i-$ th node to $j-$ th cluster head, $d_{n-CH} = \max\{(n_i, CH_j)\}$.

After deciding to which cluster it belongs, the sensor node sends registration message to inform the CH. This registration messages are transmitted to the CHs using CSMA/CA MAC protocol. During this phase, all CHs must be kept awake.

4.2.3 Schedule Creation

Our proposed protocol uses the same schedule creation used in [11]. After the registration messages are received by the cluster head from the nodes that would like to join the cluster, the cluster head creates a number of TDMA timeslots based on the number of nodes.

[1] That means the distance between the CH that send the advertisement and the non-cluster head sensor node is so close.

4.3 Steady State Phase

This phase is mainly executed to complete data transfer. Member nodes will send collected data to their CH during the assigned time slot. Each member node shuts off its own wireless communication module until its allocated time slot to save energy. However, the radio transceiver of the CH nodes must stay activated during all the transmission phase to receive the collected data from sensor nodes members.

4.3.1 Data Transmission

Sensors nodes in cluster send their data according to TDMA table, and the cluster head receives, and aggregates the data. After this, and based on the distance between the base station and the cluster head. The cluster head decides to send the aggregated data directly to the base station; or the aggregated data will be sent to the base station via inter cluster transmission, as shown in Fig. 4.

We divided the topology of network in two zones (50% of distance for each zone), so we have the near zone and the far zone as shown in the Fig. 4.

- If the cluster head located in the near zone (example: CH 1 and CH 2), in this case. The cluster head send his aggregated data directly to the base station in one single hope. We use this technique rather than to use the technique of inter cluster/multi-hop to minimize the latency/delay.
- If the cluster head is located in the far zone (example: CH_SEND 3, CH_SEND 4 and CH_SEND 5 in Fig. 4), in this case. The cluster head decides and selects an appropriate node (AP_ND) located in the nearest zone (example: AP_ND 43 and AP_ND 44) or in the far zone (example: AP_ND 55) to forward his aggregated data.

(A) The decision to choose an appropriate nearest node

We assume that there are several AP_NDs which can be selected, to choose one of them, the CH_SEND uses the following formula:

$$\text{AP\_ND}_{i-near} = \min\{(\text{AP\_ND}_1, d_1), (\text{AP\_ND}_2, d_2), \ldots(\text{AP\_ND}_{i-1}, d_{i-1}), (\text{AP\_ND}_i, d_i)\}, \tag{10}$$

where $(\text{AP\_ND}_i, d_i)$ denotes the distance between the CH_SEND and the AP_ND.

In the case where there are several of AP_NDs, which means that all sensors nodes located in the nearest zone are AP_NDs, the CH_SEND will take extra time to find the best AP_ND. Therefore, we propose to minimize the interval of research according to the Eq. (11):

$$50\% * d \leq d_i \leq 75\% * d. \tag{11}$$

Indeed the choice of an AP_ND close to the base station drains up quickly the cluster head energy reserve, for this reason we propose to balance the distance of the AP_ND for best energy saving.

After the selection of the AP_ND, the CH_SEND checks his energy according to the Eq. (12):

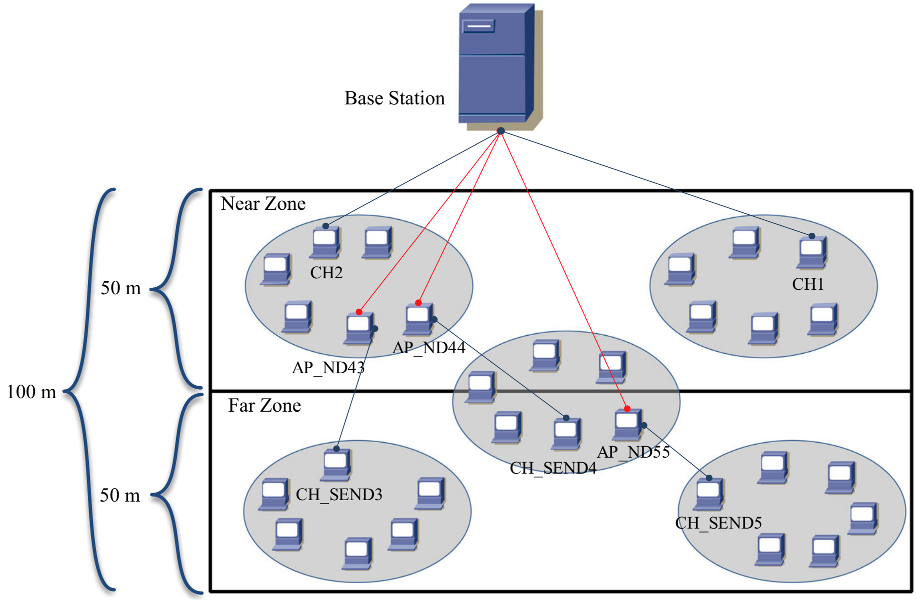

Fig. 4 Cluster transmission in PEAL

$$RE - E_{diss} \leq \frac{E_{max}}{2}, \tag{12}$$

where *RE* denotes the residual energy of the sender cluster head CH_SEND, E_{diss} denotes the energy dissipated to transmit the aggregated data to an appropriate nearest node AP_ND and E_{max} denotes the initial energy of the CH_SEND. The Eq. (13) shows how to calculate E_{diss} based on the energy model described previously:

$$E_{diss} = E_{tx}(AG\_D, d) = E_{elec} * (AG_D) + \varepsilon_{amp} * (AG_D) * d^2, \tag{13}$$

where AG_D is the size of the aggregated data, d is the distance between CH_SEND and AP_ND, E_{elec} is the energy dissipated to transmit one bit, ε_{amp} is the transmit amplifier.

Indeed, the CH_SEND will send directly his aggregated data to the AP_ND in one single hop which relays them directly to the base station (if the RE - $E_{diss} \leq E_{max}/2$).The one hop transmission minimizes the latency. In the other case, (If the Eq. 12 is not checked) the CH_SEND must choose a far AP_ND, to optimize its energy consumption.

(B) The decision to choose an appropriate far node

The selection of a far node as AP_ND is applied in the case where the CH_SEND has less than 50% of remaining battery reserve. Therefore, the CH_SEND must choose an AP_ND located in a far zone based on the Eq. 14:

$$\text{AP\_ND}_{i-far} = \begin{cases} \min\{(\text{AP\_ND}_1, d_1), (\text{AP\_ND}_2, d_2), \ldots(\text{AP\_ND}_{i-1}, d_{i-1}), (\text{AP\_ND}_i, d_i)\} \\ \textit{and} \\ 25\% * d \leq d_i \leq 50\% * d. \end{cases} \tag{14}$$

The CH_SEND will choose the AP_ND_{i-far} located between 25% and 50% of the overall distance, we use this technique to save energy.

After the CH_SEND chooses the AP_ND_{i-far}, it sends its aggregated data directly to the AP_ND_{i-far} in one single hop, the AP_ND_{i-far} receives the aggregated data from CH_SEND and relays them directly to the base station in one single hop to minimize the latency.

In the case where no AP_ND (far or near) are selected, the CH_SEND will send its aggregated data directly to the base station. A working flowchart of PEAL is shown in Fig. 5.

5 Simulation

5.1 Simulation Environment

The evaluation of our protocol PEAL is performed using the network simulator NS2.34. Our experimental model is built on 100 nodes distributed randomly on a square surface of 100×100 m^2, Fig. 6 illustrates the network topology. We assume that all the nodes have a fixed position throughout the simulation period.

The simulation parameters used in our simulation model are summarized in the Table 1.

5.2 Simulation Results

All simulation results presented in this section are average of 10 runs.

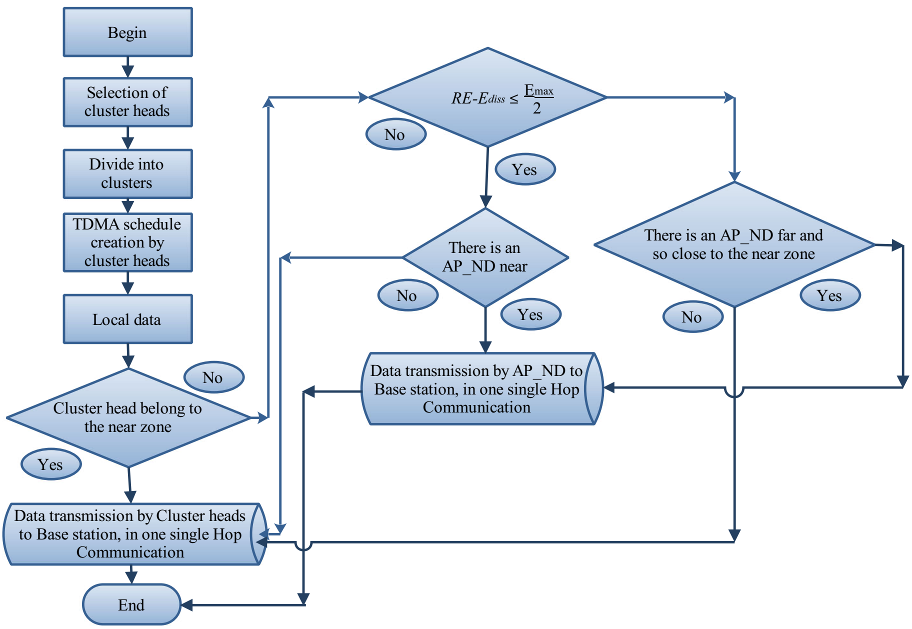

Fig. 5 Working flow chart of PEAL

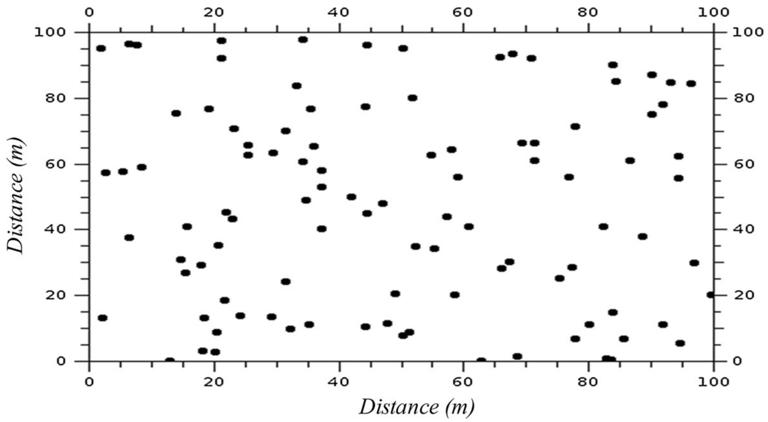

Fig. 6 Network topology

Table 1 Simulation Parameters

Parameter	Value
Surface of the network	$100 \times 100\ m^2$
Location of the BS	(50,175)
Number of nodes	100
Number of CHs	5
Initial energy of nodes	2 J
Size of data packet and	500 Byte
Size of control packet	128 Byte
E_{elec}	50 nJ/bit
εfs	$10\ nJ/bit/m^2$
Routing protocols	LEACH, PEAL

The first evaluation step is to analyze the behavior of our protocol PEAL in terms of the energy consumption. We measured the dissipation energy for each round as the simulation progresses. The Fig. 7 illustrates the energy consumption of our protocol PEAL, in order to show the performance of our protocol we compared its energy consumption over the simulation time with the protocol LEACH.

According to the Fig. 7, PEAL preserves the energy reserves and consumes all the energy of the network after 950 s. In the other side LEACH consumes all the network energy after 650 s. Consequently, PEAL extends the network life time about 47% compared to LEACH.

The second evaluation step of our protocol is to analyze the number of alive nodes over the simuation time, for this we mesured the number of the alive nodes for each round. The Fig. 8 illustrates this evaluation. Also we compared PEAL with LEACH to check its performance.

According to the Fig. 8, the first node death occurred after 400 s in LEACH and 450 s in PEAL. This result confirmes that PEAL protocol delays the first node death by 12.5% copared to LEACH protocol. After 400 s of simulation time we observe that all the nodes die quickly in LEACH, however the nodes die slowly in PEAL as shown in Fig. 8, for example when all the nodes in LEACH die at 650 s there are still 65 nodes alive in PEAL protocol.

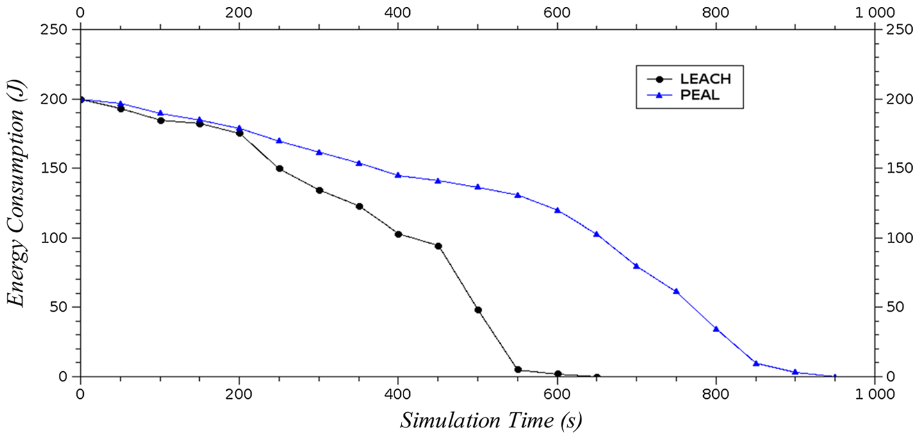

Fig. 7 Energy consumption over the simulation time

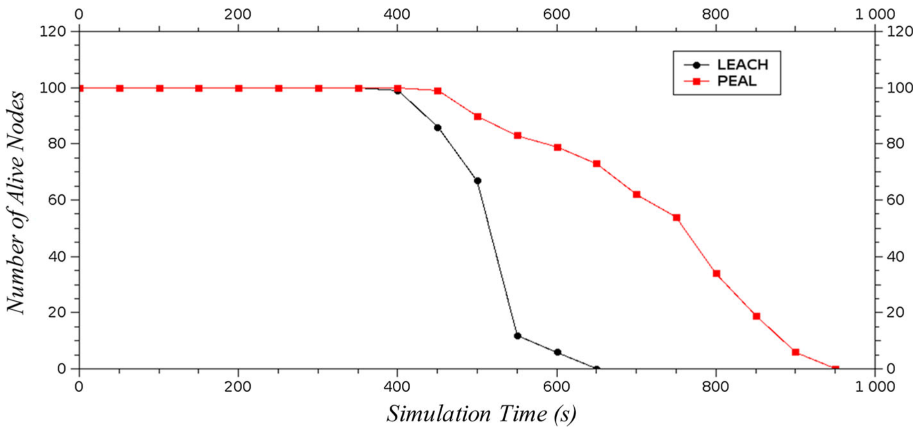

Fig. 8 Number of alive nodes over the simulation time

The third evaluation step is to analyze the behavior of our protocol in terms of latency, for this reason we used the formulas 15 and 16 to measure the latency for each transmission round.

Indeed, latency is the amount of time a message takes to travel between sources (CH) until destination (BS). PEAL works in rounds, for each round there are five CHs, when the BS receives a message it compares the reception time with the transmission time extracted from the message.

$$latency_{sum} = \sum_{i=1}^{5} (T_{receive} - T_{send}), \quad (15)$$

$$Latency_{round} = \frac{latency_{sum}}{5}. \quad (16)$$

In Fig. 9 the latency performance of PEAL was compared to the LEACH protocol.

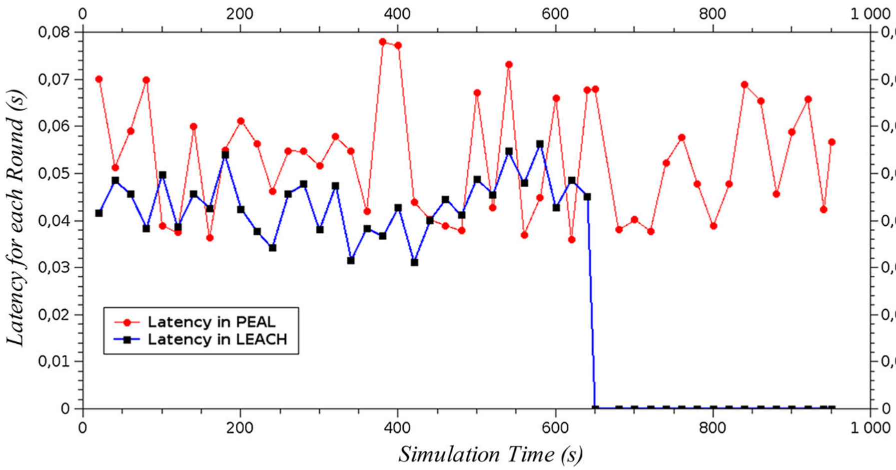

Fig. 9 Latency in both of routing protocols PEAL and LEACH over simulation time

As shown in Fig. 9, the latency variation in PEAL protocol is between 36 and 80 ms, while in LEACH protocol it is between 32 and 56 ms. We can notice in Fig. 9 that the end-to-end latency in PEAL protocol is acceptable for emerging applications in WSN which require real time QoS (Quality of Service), such as multimedia applications. Indeed, PEAL protocol introduces 36% more latency compared to LEACH protocol, which is also acceptable compared to the energy saving and the network lifetime improvement.

6 Conclusions

One of the most important constraints in WSN is the low power consumption requirement. Therefore, designing energy-aware protocols becomes an important factor for extending the network lifetime. However, their main challenge is to have efficient mechanisms to achieve the trade-off between increasing the network lifetime and accomplishing acceptable transmission latency. Based on the above mentioned constraints, we designed PEAL, a new protocol for cluster-based wireless sensor networks. Our simulation results showed that PEAL can extend the network life time about 47% compared to the classic protocol LEACH while introducing acceptable transmission latency.

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Faouzi Hidoussi has received his master degree in Computer Science from Batna University, Algeria, in 2013. He is currently a collaborating researcher at the laboratory Networking and Distributed Computing Laboratory of International Islamic University Malaysia. His research interests include Wireless Communication, security and Sensor Networks. He has served as a TPC member in many international conferences. Mr. Hidoussi is a steering committee chair and member in AWICT 2015 Tunisia, ICCMIT 2015 Prague Czech Republic. Mr. Hidoussi is the founder of two international conferences; International Conference on Advanced Wireless, Information, and Communication Technologies (AWICT 2015 Tunisia) and international conference on Intelligent Information Processing, Security and Advanced Communication (IPAC'2015 Algeria) he serving in these conferences as a program chair. Mr. Hidoussi is also a guest editor in International Journal of High Performance Computing and Networking, International Journal of Intelligent Engineering Informatics, International Journal of Information and Communication Technology, and International Journal of System Dynamics Applications (IJSDA).

Homero Toral-Cruz received his Ph.D. and M.S. degrees in Electrical Engineering, Telecommunication option from Center for Research and Advanced Studies of the National Polytechnic Institute (CINVESTAV), Jalisco, Mexico, in 2010 and 2006, respectively. He received his BSc degree in Electronic Engineering from "Instituto Tecnológico de la Laguna", Coahuila, Mexico in 2002. He is currently an assistant professor at Sciences and Engineering department at the University of Quintana Roo, Mexico. Prior to holding this position, he served as an assistant researcher at Electrical Engineering department, Telecommunication section in CINVESTAV, Jalisco, Mexico. His research interest includes network measurement, IP technologies, network security and wireless sensor networks. He has served as guest editor of some high quality journals. In addition, he has served as a chair, organizing committee member and technical program committee member for many international conferences and workshops. Dr. Toral is also an active reviewer of some renowned international journals. Furthermore, he has been awarded a national recognition as a researcher (SNI level 1) by CONACYT and has been elected as member of the Mexican Academy of Sciences (AMC).

Djallel Eddine Boubiche received his HDR diploma (Habilitation to conduct research) in 2015 from Batna 2 University and his Ph.D in Computer Science from UHLB University, Algeria, in 2013. He received the Magister degree in Industrial Informatics from El Hadj Lakhdar University, Algeria, in 2008 and the B.Eng degree in Computer Engineering from UHLB University, Algeria, in 2004. He is currently an Associate Professor at the Computer Sciences Department of Batna 2 University, Algeria. He was also the Vice Director of the Computer Sciences Department and a member of LaSTIC Laboratory. He is a member of the scientific committee in the Computer Sciences Department of Batna 2 University from November 2013. His research interests include Wireless Communication, Emended System, Intelligent Multi-Agent System, Distributed Computing and Sensor Networks. Dr Boubiche research has been published in various renowned international journals and conferences, such as the International Journal of Sensor Networks (IJSNet), IEEE Communications Letters, Wireless Personal Communications, Telecommunication system journal and IEEE ISCC conference, etc. He frequently serves as a program committee member such as: ICACIS'12 ICCMIT'15, ECARS'15 and ISNCC 2016. He was also the program chair of the AWICT'15 and IPAC'15 international conferences and the general chair and co general chair of BDAW'16 and ICC'16. Dr Boubiche is the guest editor of several special issue organized in international indexed journals such as: special issue entitled High-Performance Information Technologies for Engineering Applications organized in the international Journal of Computational Science and Engineering, the special issue entitled Advanced Information Processing in Communication organized in the international Journal of Computational Science and Engineering, special issue entitled Artificial Intelligence and Knowledge Computing organized in the international Journal Artificial Intelligence and Soft Computing and special issue Advanced Industrial Wireless Sensor Networks and Intelligent IoT, organized in IEEE Communications Magazine. He is also a reviewer of some renowned international journals.

Rafael Martínez-Peláez received Ph.D. degree from the Technical University of Catalonia in 2010. He is an associate professor in the "Facultad de Tecnologías de Información, Universidad de la Salle Bajío", León, Mexico. He has served as TPC member of many international conferences and workshops. He is a member of the National System of Researchers (SNI) of the National Mexican Science Council (CONACYT). His research interests include authentication technologies, smart cards, security issues on electronic services, and WSN.

Pablo Velarde-Alvarado is a Research-Professor at the Area of Basic Sciences and Engineering of the Autonomous University of Nayarit. He received the B. Tech. degree in electronics engineering from the Autonomous University of Guadalajara (UAG), in 1993, and the M.Sc. and Ph.D. degrees in electrical engineering from the Center for Research and Advanced Studies (CINVESTAV-IPN) in Guadalajara City, in 2001 and 2009, respectively. He is a member of the National System of Researchers (SNI). His research interests include IP-Traffic Modeling, design of concise behavior models for Entropy based Intrusion Detection Systems and WSN.

Romeli Barbosa received Ph.D. and M.S. degrees in Energy Engineering option from National Autonomous University of Mexico, in 2012 and 2007, respectively. He received the B.Sc. degree in Engineering in Energy Systems from "Quintana Roo University", Mexico in 2004. He is currently an Assistant Professor at Sciences and Engineering department at the Quintana Roo University, Mexico. He has been awarded a national recognition (SNI member) as a researcher by CONACYT. His research interest includes numerical simulation and design of Catalyst layer and PEM Fuel Cells. Dr. Barbosa, at present is author of nine international papers and is involved in five innovative pilot projects, mainly in the fields of development of new devices for power generation with high power density.

Freddy Chan received the B.S. degree in electronic engineering from Mérida Institute of Technology, Mérida, México, in 1996 and the M.S. and Ph.D. degrees in electronic engineering from the National Center for Research and Development of Technology, Cuernavaca, México, in 1999 and 2008, respectively. He is currently a Professor with the Department of Sciences and Engineering, University of Quintana Roo, Chetumal, México. He is a member of the National System of Researchers (SNI) of the National Mexican Science Council (CONACYT). Winner of the Merit to the trajectory in Investigation in 2013, by the State Council of Science and Technology. He has been awarded the National Energy Prize in 2005, by the Department of Energy in the Innovation category. His research interests include home automation, power electronics, energy conversion and reliability issues in photovoltaic systems.