Energy Efficient Routing in Wireless Sensor Networks: A Comparative Study on LEACH Protocol and its Successors

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***Abstract* — Wireless Sensor Networks (WSNs) are among the most important fields of Wireless Computing. Yet, the network lifetime of WSNs is very limited because the energy reserves of their wireless nodes are extremely restricted. Thus, the greatest challenge for deploying WSNs is the minimization of energy consumption. In a WSN the greatest part of energy consumption takes place during data routing. That is why the most effective way to reduce energy consumption in WSNs is to perform energy efficient routing. This work focuses on LEACH (Low Energy Adaptive Clustering Hierarchy), which is one of the pioneer protocols of this kind, along with the main successors of LEACH. A theoretical comparison of these protocols, based on various metrics, using either single hop communication or multi hop communication is made. Also, three of these protocols are compared with LEACH through simulation tests performed. Finally, corresponding concluding remarks are drawn.**

Keywords— ***Wireless Sensor Networks, LEACH, Energy Conservation, Hierarchical Protocol, Energy Efficient Routing***

I. INTRODUCTION

A WSN is a group of wirelessly interconnected devices, called nodes that have sensing, processing and communication capabilities. In every WSN at least one node called base station (BS) has enhanced capabilities [1] [2]

As illustrated in Fig. 1, the main components of a node are:

- Sensing unit: It contains sensors that are needed in order to acquire necessary ambient data.
- Processing unit: It contains a memory unit and a programmable unit to control the node operations.
- Communication unit: It contains a transceiver, which is a device, that performs both the transmission and reception of radio signals.
- Power unit: This module provides the necessary energy to the node. In most of the cases, this unit is a battery.

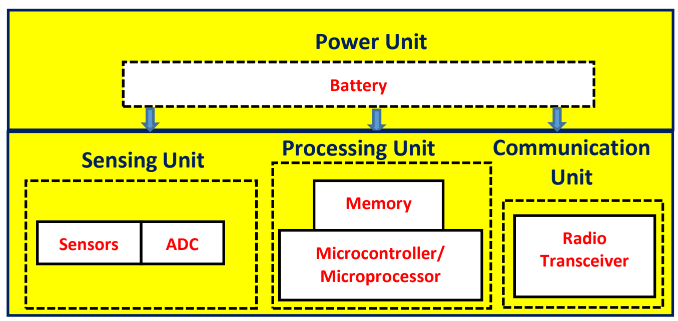

Fig.1 The main components of a wireless sensor node

The collaborative use of these devices enables WSNs monitor the conditions in wide areas of interest [1]. Actually, the initial use of WSNs was for military purposes during the Vietnam War. Nowadays, WSNs have a endlessly growing collection of applications [2], not only in military [3], but also in environmental [4], flora and fauna [5], health [6], industrial [7], transportation [8], surveillance, [9], security [10] and various other urban sectors of human activity.

Yet, despite the numerous advantages provided by WSNs, the use of this kind of networks is obstructed due to various problems that cause serious failures or even network collapse.

For instance, WSNs are particularly vulnerable, because they usually consist of plenty of scattered nodes that may serve for malicious intruders as access points to the network [11]. Also, due to either interference or buffer overflow, congestion is more frequent in WSNs than in wired networks [12]. That is why, the use of congestion avoidance and congestion control methods is necessitated [13]. Also, connectivity loss is very frequent in WSNs due to interference, malfunctions, and energy exhaustion of the nodes. Moreover, the attainment of maximum coverage and / or /k-coverage has to be achieved. That is why special control

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schemes must be used [14], [15], [16]. High QoS is also very important but difficult to attain, due to inherent problems of wireless communications, thus imposing the use of special routing protocols [17]. When handling with multimedia data, special control schemes must be applied [18], [19], [20].

Yet, the main problem in WSNs, is the limited lifetime of the nodes' batteries. The energy inadequacy causes loss of communication among nodes, at the end, network collapse. In WSNs the greatest part of energy consumption occurs during data routing. That is why the most effective way to reduce energy consumption is to perform power control [21] along with energy efficient routing [22]. In the cases where energy efficiency is pursued along with other performance metrics, multiobjective optimization is needed [23].

The rest of this article is organized as follows. In section II the theoretical background regarding the patterns of traffic and the categories of energy efficient routing protocols is set. Section III focuses on LEACH protocol. Section IV presents and discusses LEACH based protocols. In section V the results of simulation tests performed are both presented and discussed. Finally, in section VI concluding remarks are drawn.

II. THEORETICAL BACKGROUND

A. Traffic Patterns in WSNs

The study of data traffic in WSNs is very important and in many times quite complex, due to the great population of nodes and the wide areas of network fields. Actually, in WSNs, there are multiple routes for data forwarding and transmission, because the network nodes send messages both to other neighboring nodes or/and the base station and while the base station sends messages to all network nodes too. The traffic can be categorized as single hop or multi-hop.

Single hop traffic occurs only when neighbor nodes are communicating between each other.

The multi-hop traffic, as shown in Fig. 2, can be categorized to the following patterns [24]:

- Local communication: For data transmission between two adjacent nodes directly.
- Point – to – point: A node sends random messages to other node.
- Convergence: The data are sent to a relaying node which next forwards the packet to the base station without applying any aggregation function.
- Aggregation: Data from multiple nodes are forwarded to cluster-head or base station as a single packet.
- Divergence: A sink node or base station sends back to all sensor nodes messages or queries.

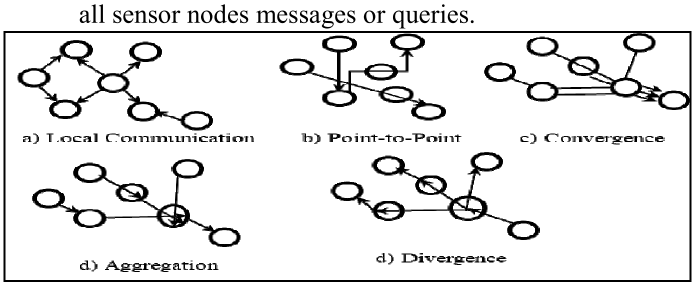

Fig. 2. Traffic patterns specific to WSNs

B. Categories of Energy Efficient Routing Protocols in WSNs

As shown in Fig. 3, the protocols for energy efficient routing in WSNs can be classified into four major categories (i.e. Communication Model, Network Structure, Topology Based, Reliable Routing), and several subcategories [25] :

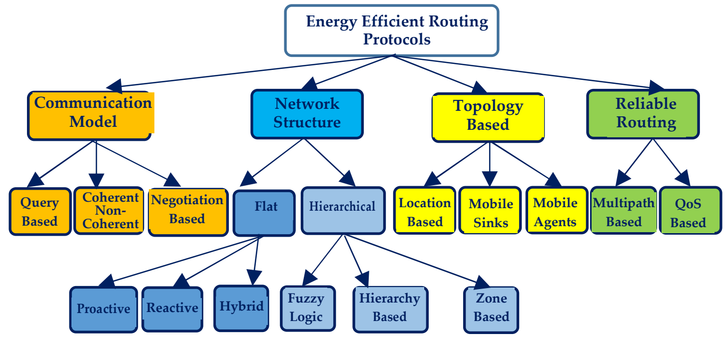

Fig. 3 Classification of Energy Efficient Routing Protocols in WSNs [24]

Specifically, the protocols grouped in the Communication Model category are differentiated according to the policy that is used to perform data exchange. The existence or absence of a hierarchy within nodes is the key characteristic of the protocols that are grouped according to the Network Structure. Protocols in Topology category are classified according to the topological information that is used in order to perform data routing. Finally, the protocols in Reliable Routing class are categorized depending on whether they perform data exchange based on QoS metrics or multipath routing.

C. Protocols Based on Network Structure

Protocols in this category are further classified in two subcategories, i.e. Flat and Hierarchical. Flat protocols are intended for small WSNs with no expansion abilities, where there is no hierarchy among the network nodes. In Hierarchical protocols, the network nodes are organized in groups, named clusters, with an elected cluster head (CH) for each one. CHs are used for high level communication with the BS, while nodes exchange data with neighboring nodes and their CH.

III. LEACH PROTOCOL

LEACH is a pioneer hierarchical routing protocol for WSNs [26]. The main idea of this protocol is to group the network nodes into clusters and provide a mechanism that balances the procedure of CH election in a way that prevents a node from being continuously selected as a CH.

LEACH consists of two phases, i.e. the set-up phase and the steady state phase.

The main aim of the set-up phase is the selection of the CH, the cluster formation and the assignment of a TDMA (Time Division Multiple Access) schedule by the CH to the member nodes. At the beginning and in order to elect the appropriate node as a CH, all nodes participate and create a random priority value which varies between 0 and 1. If this number is lower than a specific threshold $T(n)$, this node becomes a CH. The value of the threshold $T(n)$ is calculated by the following formula:

$$T(n) = \begin{cases} \frac{P}{1-P\cdot\left(r \cdot mod \cdot \left(\frac{1}{P}\right)\right)} & \text{for } n \in G, \\ 0 & \end{cases} \quad (1)$$

where P is the percentage of the nodes to become CH, r is the current round and G is the total number of the nodes that have not been elected as CH in $1/P$ previous rounds. It is obvious that a node that has been a CH in r round cannot be elected again in the next $1/P$ rounds. This leads to a balanced way to choose a node as a CH and the loss of energy among the nodes is distributed smoothly.

The optimal percentage of CHs is found to be 5%. As soon a node becomes a CH, it transmits an advertisement message to other nodes. Each one of the rest network nodes chooses to join the cluster of the CH whose advertisement message has been received with the highest power and it sends a reply message back to the specific CH.

This procedure leads to the creation of the clusters with the relative CHs. Then the CH creates a TDMA schedule and transmits this schedule to the nodes member of this CH. In this way, each node knows exactly the when to transmit any information and the TDMA schedule is used in order to avoid any congestion during the data transmission period. The set-up phase is completed only when each node is aware of the TDMA schedule. As soon as this happens the steady state phase begins.

During the steady state phase, data transmission between nodes and CH and CH to BS are made. In the first case, the nodes send data to CH only during the timeslot specified by the TDMA schedule. When this node transmits data, the rest node that belongs to the same CH is in sleep mode. This leads to congestion avoidance and to energy conservation of the node's battery. After the CH has collected the data from the cluster nodes, it sends it to the BS, by using a TDMA schedule.

As mentioned above, LEACH balances the procedure of CH election among network nodes, thus extending the network lifetime. In addition, global network knowledge is not required.

Also, the use of TDMA schedule avoids data collision during transmissions. On the other hand, the energy residues of nodes are not taken into consideration during the CH election procedure. Thus, the probability of a node to become a CH is the same for both nodes with low level of energy and the nodes with high energy reserves. Also, LEACH is not suggested for WSNs deployed in large areas because it uses single hop routing. In addition, dynamic clustering creates overhead that may shrink gain in energy consumption.

IV. LEACH BASED HIERARCHICAL ROUTING PROTOCOLS

Numerous energy efficient routing protocols that are based on LEACH have been proposed. They can be differentiated depending on the type of communication between the CH and the BS, as single hop and multiple hop.

A. LEACH successors using single hop communication

In LEACH based protocols that use single hop communication the CHs directly send their data to the BS. Actually, one hop communication is proper only in small WSNs. Some of the most popular protocols of this kind are as follows:

Centralized LEACH (LEACH – C) [27] is a centralized protocol [25] in which the BS performs all decisions regarding the formation of clusters, the CH selection, and the dissemination of information thus reducing overhead for nodes. Also, the BS calculates the average energy of the cluster nodes in every round in order to allow only nodes having more than the average energy participate in the CH selection process.

LEACH – Deterministic Cluster Head Selection (LEACH-DCHS) [28] uses a modified version of threshold. Specifically, for every node $T(n)$ of LEACH is multiplied with the ratio of the current energy to the initial energy of this node.

Security Based LEACH (S – LEACH) [29], is the first protocol that offers security from outsiders' attacks by authenticating the messages' senders and checking whether the messages are new or old.

More Energy Efficient LEACH (ME – LEACH) [30] shortened the communication distances among nodes and improved the load balance on them.

Time Based LEACH (TB – LEACH) [31] presented the idea of using a threshold that is based on a time interval, which on turn is set through a timer used by each individual node.

Advanced LEACH (A – LEACH) [32] calculates the threshold as the sum of two other metrics, i.e. the current state probability and the general probability.

Threshold LEACH (T – LEACH) [33] proposed the use of an energy threshold so that a new CH selection process is initiated only when the residual energy of the existing CH becomes lower than the threshold energy.

In Improved LEACH (I – LEACH) [34] the CHs are selected by considering for every node its residual energy, the number of its neighboring nodes and its distance from the BS.

In Energy Harvested Aware LEACH (EHA – LEACH) [35] the use of energy harvested sensor nodes is proposed, while the nodes that combine low energy consumption and high capacity of energy harvesting are more likely to elected as CHs.

Another well-known protocol, which provides high energy efficiency and expands the lifetime of WSNs, is the so called Modified LEACH (Mod – LEACH) [36]. This protocol proposes the use of an energy threshold for the procedure of the creation of clusters and the selection CHs. Specifically, at the end of each round the current CH is replaced only if it has less energy than this threshold. Additionally, this protocol uses lower power signals intra cluster communication (i.e. inside the cluster) and higher power signals for inter cluster transmission (i.e. among CHs).

Table 1 displays the comparison of LEACH with its abovementioned single hop successors in terms of specific metrics [37]

Table 1: Comparison of LEACH with some of its single hop successors

Name of protocol	Overhead	Scalability	Energy Efficiency	Complexity	Delay
LEACH	High	Low	Moderate	Low	Small
LEACH-C	Low	Low	High	Moderate	Small
LEACH-DCHS	High	Low	High	Moderate	Small
SLEACH	High	Moderate	Very high	High	Small
ME-LEACH	Low	Low	Moderate	Low	Small
TB-LEACH	High	Moderate	Moderate	High	Small
ALEACH	High	Moderate	High	Very high	Small
T-LEACH	Moderate	High	High	High	Small
EHA-LEACH	High	High	Very high	High	Small
MOD-LEACH	Low	Moderate	High	High	Small

B. LEACH successors using multiple hop communication

In LEACH based protocols that use multiple hop communication, the CH sends data to the BS by using intermediate nodes. These nodes could be either simple nodes, or other CHs. In this type of communication the distance between initial and final nodes is a key factor. If the distance is above a threshold distance, then the energy consumption increases with distance d to the power four: d^4. The main aim of multiple hop communication is to keep the distance as minimum can be or below of this threshold distance. Some of the most popular protocols of this kind are as follows:

In Multihop LEACH (MH – LEACH) [38] the set-up phase is similar to that of LEACH. In the steady state phase, CHs located far away from the BS are selected as intermediate nodes to convey data to the BS while the CHs that are near to the BS transmit data directly to the BS. MH-LEACH is more energy efficient and highly scalable than the basic LEACH, but due to the multi-path transmission through relay nodes has become more complex and increases network overhead.

In Energy LEACH (E – LEACH) [39] nodes with higher residual energy are chosen as CHs. A CH forwards data to its nearest neighboring node. This procedure is repeated until the CH which is the closest to the BS receives the data. Finally, this CH sends the data to the BS.

In the Advance Multihop Low Energy Adaptive Clustering Hierarchy (LEACH – L) [38] the CHs located away from the BS select other CHs as their relay nodes, by taking into account the distance of these CHs to the BS and their residual energy. The CH located close to the BS transmits data directly to the BS. The requirement of location information for each node adds complexity and overhead.

In Multihop Routing LEACH (MR – LEACH) [40] CHs are selected, according to their residual energy and position, in the first level (i.e. in a one hop distance from the BS), the second level (i.e. in a one hop distance from the first level CHs), and the rest levels. Corresponding TDMA schedules are used.

Another protocol that was based on LEACH protocol is the balanced LEACH, so called LEACH – B [41]. This protocol improves the cluster selection procedure, by having as critical criterion the remained energy of the nodes. Based on [42], the optimal percentage of CHs is between 3% and 5%. For the selection of CHs it takes into account both the desired percentage of CHs and the remaining energy of nodes. Actually, some CHs are elected randomly based on their residual energy level. If the number of the randomly selected CH is lower than the product n x p (where n: the number of nodes and p: the percentage of the desired CHs), then some regular nodes are selected as CHs.

If this number is larger than the product n x p, then CHs with low energy are rejected in order to let the number of CHs be equal to n x p. In order to achieve this, all CHs are sorted in descending order based on their residual energy. The CHs ranked lower than n x p are converted to normal nodes. LEACH-B improves the cluster energy-load balance and reduces the energy consumption of sensor nodes. Message overhead, scalability and complexity are the main drawbacks of this protocol.

Table 2 compares the abovementioned multiple hop LEACH successors [37].

Table 2: Comparative analysis of multiple hop LEACH and its successors

Name of protocol	Overhead	Scalability	Energy Efficiency	Complexity	Delay
MH-LEACH	Moderate	High	High	High	High
E-LEACH	Low	High	High	High	High
LEACH-L	High	High	High	High	High
MR-LEACH	High	High	High	High	High
LEACH-B	High	Low	High	Moderate	Moderate

V. Simulation Tests

Following the aforementioned theoretical analysis, a simulation procedure was established in order to indicatively compare the operation of LEACH, MR-LEACH, LEACH-B, and MOD-LEACH. The simulation parameters used in the tests performed in MATLAB are shown in Table 3.

Table 3: Parameters of simulation tests performed

Dimensions of network field (m x m)	200 x 200
No. of nodes	100
Location of BS (m, m)	(100,100)
Initial node energy (J)	
Transmission energy (J/bit)	$5*10^{-8}$
Reception energy (J/bit)	$5*10^{-8}$

In Fig. 4 the nodes remaining alive are illustrated vs simulation rounds.

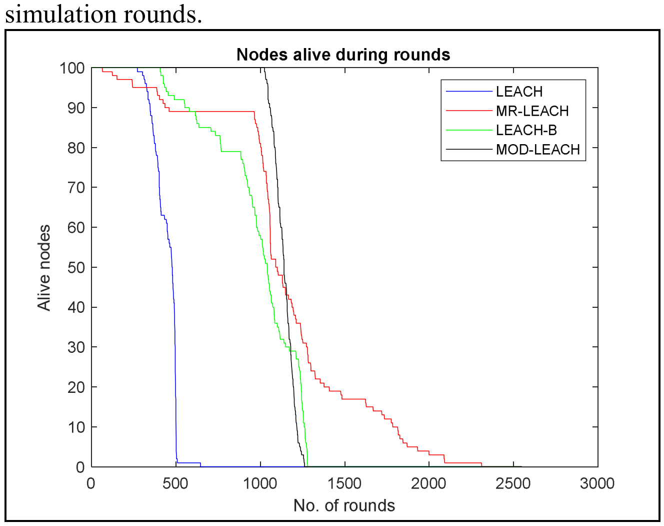

Fig. 4: Number of nodes alive vs simulation rounds

Table 4 shows the depletion time of the first, the tenth and the last node for each one of the protocols that are compared.

Table 4: Depletion time (in simulation rounds) of first, tenth and last node

Name of Protocol	Depletion of first node (rounds)	Depletion of 10% of nodes (rounds)	Depletion of last node (rounds)
LEACH	272	347	646
MR-LEACH	65	453	2311
LEACH-B	407	553	1280
MOD-LEACH	1025	1055	1262

The examination of these simulation results shows that all three LEACH based protocols achieve longer network lifetime than LEACH. MR-LEACH resists less than the other protocols regarding the first node dissipation, but more than all of the protocols in comparison regarding the last node dissipation. On the other hand, MOD-LEACH keeps all nodes alive for greater time interval than the other three protocols.

In Fig. 5 the number of packets sent to the BS is illustrated vs simulation rounds.

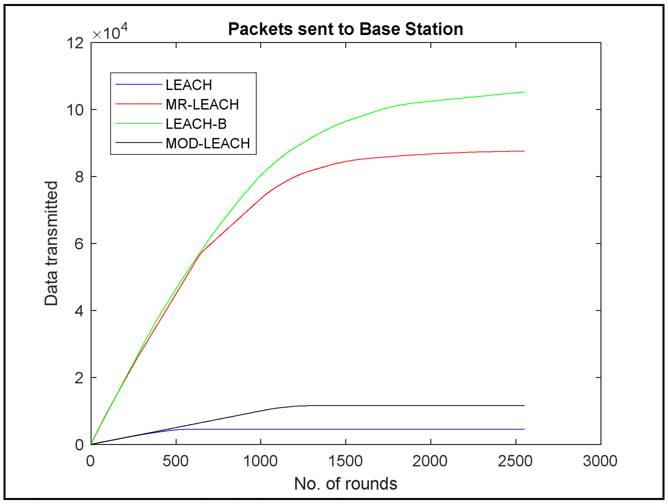

Fig. 5: Data sent vs simulation rounds

Table 5 shows for each one of the four protocols that are compared the total numbers of bits sent to the BS.

Table 5: Data sent to the BS (in bits)

Name of Protocol	Packets sent
LEACH	4.479
MR-LEACH	87.625
LEACH-B	105.302
MOD-LEACH	11.544

It is observed that the most data are sent with LEACH-B while the less data are sent when LEACH is used.

VI. Conclusions

In this paper, a comparative study on LEACH and three LEACH based hierarchical energy efficient routing protocols (i.e. MR-LEACH, LEACH-B, and MOD-LEACH) was performed. It was exhibited that all three successor protocols of LEACH perform better than LEACH itself. It was also evinced that the selection of the most suitable protocol of this type depends on the type of application under examination and the metrics that are associated with it.

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