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Multi-hop cluster based routing approach for wireless sensor networks

Mounir Arioua*, Younes el Assari, Imad Ez-zazi, Ahmed el Oualkadi

*Laboratory of Information and Communication Technologies, National School of Applied Sciences, Abdelmalek Essaadi University, Tangier,
BP 1818, Morocco*

Abstract

One of the key challenges in wireless sensor networks is the efficient usage of restricted energy resources in battery operated sensor nodes. Clustering remains the most effective routing approach used in WSN. Low Adaptive Clustering Hierarchy (LEACH) protocol is an efficient routing approach which has been widely adopted and enhanced to improve the lifespan of deployed sensor networks. However, latterly, clustering algorithms have shown their limitation in extending the network lifespan. In this paper, we propose a new clustering approach based on a combination of LEACH and MTE protocols. The adoption of multi-hop communication instead of direct communication in cluster filed has optimized the communication in the network. The simulation results illustrate the energy efficiency of the multi-hop cluster based routing approach. The proposed method achieves significant improvement in term of network lifespan and provides enhanced energy performance for wireless sensor networks.

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Keywords: Wireless Sensor Networks; Clustering; Multi-hop communications; MTE; LEACH; Energy efficiency.

1. Introduction

Wireless sensor networks (WSNs) are special ad hoc networks that provide the monitoring of physical world through numerous tiny, cheap and smart sensor nodes dispersed in desired area of interest¹. These sensor nodes are autonomously accommodated to sense, process and wirelessly convey environment conditions to a base station². WSN has been widely used in different applications such as habitat and industry monitoring, medical diagnosis,

* Corresponding author. Tel.: +212-539-688-027; fax: +212-539-994-624.
E-mail address: m.arioua@uae.ma

environment monitoring and agriculture³⁻⁵. Wireless sensor nodes are commonly powered by restricted capacity batteries which replacement is delicate in hostile environment where hundreds of nodes are randomly deployed. Therefore, nodes must be able to operate in low power modes to increase the longevity of their power supplies. Hence, energy optimization and efficiency are extremely important factors to be considered in WSN⁶.

Among energy consumption sources in a sensor node, energy used in wireless data communication has the most critical impact. Routing is one of the crucial energy efficient techniques employed in WSN that aims to lower the communication energy burden^{7,8}. Cluster-based routing architectures are widely used in wireless sensor network due to their energy efficiency and load balancing in the network⁹⁻¹¹. Sensor nodes in cluster architecture are grouped into clusters in which a cluster head (CH) is elected and group of source nodes are directly attached to the cluster head.

Generally, a cluster network employs single hop routing in each cluster¹². The one-hop clustering can reduce the energy consumption of communication by forwarding source nodes data to the cluster head via one hop. However, when communication distance increases, single hop communication consumes more energy and becomes less energy efficient method. For a large network, where inter-node distance is important, multi-hop communication is energy efficient approach^{13,14}. For this reason, we proposed to employ a multi-hop communication in clustered routing architecture to mainly prolong the network lifetime by saving transmission energy. The proposed approach combined multi-hop and clustered routing approach. It is based on low energy adaptive clustering hierarchy (LEACH) and minimum transmission energy (MTE) protocols. Simulation results in MATLAB tool show that the performed approach ameliorates the network lifespan and minimizes the energy consumption of the sensor nodes. An efficiency comparison with LEACH protocols is carried-out.

The remainder of this paper is organized as follows. In section 2, the energy model used in this work is described. Section 3 exhibits the multi-hop clustered based routing approach. In section 4, simulations and results are analysed and discussed. Finally, section 5 concludes the paper.

2. Radio energy model

In this work, we use the first order RF model to estimate the energy consumption of different nodes and the whole network lifetime¹³. This model which is thoroughly discussed in¹³, introduces the energy expended to send and receive L -bit message over a distance d taking into account free space propagation and multi path propagation models. The transmission energy in free space model is proportional to distance d^2 , for multi path propagation model this energy is proportional to distance d^4 due to different paths that take the transmitted signal to reach the receiver¹⁵. The energy model for transmission and reception is shown in Figure 1.

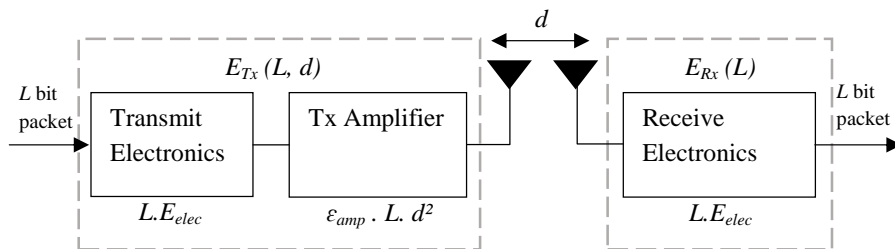


Fig. 1. First order energy model¹³

The energy consumed to send data of L bit packet over a distance d from a node to a cluster head or a base station is calculated according to equation (1).

$$E_{Tx}(L, d) = E_{tx-elec}(L) + E_{tx-amp}(L, d) \quad (1)$$

The energy expended for free space propagation E_{Tx-fs} is described by:

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

The energy expended for multi-path propagation E_{Tx-mp} is given by:

$$E_{Tx-mp}(L, d) = E_{elec} \cdot L + \epsilon_{mp} \cdot L \cdot d^4 \quad (3)$$

Where E_{elec} is the energy dissipated by electronic circuit to send and receive L bits. The amplifier parameters ϵ_{fs} and ϵ_{mp} present the energy per bit required in the transmit amplifier to transmit L -bit message with adequate SNR over a distance d^2 for free space propagation model and d^4 for multi path propagation model, respectively.

The energy expended to receive L -bit message is defined as:

$$E_{Rx}(L) = E_{elec} \cdot L \quad (4)$$

By equating formula (2) and (3), we obtain the crossover distance d_0 (Equation 5) that defines the propagation transition from direct path to multipath model:

$$d_0 = \sqrt{\frac{E_{fs}}{E_{mp}}} \quad (5)$$

If the distance between the transmitter and the receiver is larger than the crossover distance d_0 , the multi-path model is employed. Otherwise, the free space model is adopted to measure the energy dissipation¹⁴

3. Multi-hop clustered based routing approach

Clustering in wireless sensor networks is an efficient architecture to manage the sensor network efficiently^{16,17}. LEACH is a commonly used clustering protocol in which cluster heads and their attached source nodes are periodically changed in order to enable efficacious balance. However, LEACH requires all source nodes to forward their data directly to the associated CHs which affect source nodes energy due to the significant cost of long distance transmissions¹⁷. Therefore, source nodes that are far away from the cluster head drain hastily their energy than other nodes. To resolve this energy constraint, the proposed approach employs multi-hop inter-nodes communication using MTE algorithm where source nodes forward their data to the cluster heads through intermediate nodes inside each cluster. Each source node in the cluster sends its message to the closest node on the way to the cluster head in order to minimize the transmission energy.

Considering the communication distance and the network density requirements, the network structures assuring direct communication between any member node and CHs may not be practical for large scale sensor networks¹⁸. Consequently, for a large scale wireless sensor network there is a need for multi-hop communication structure which does not limit the cluster size and its area coverage. MTE algorithm is an effective multi-hop protocol widely adopted in wireless sensor network¹⁹. It consists of transmitting data by using other nodes that act as routers along with environment sensing. The intermediate nodes among the clusters route other sensor's data that are destined for cluster heads. The routers nodes are chosen such that the transmit amplifier energy is minimized. In each cluster, source nodes calculate the distance to the cluster heads by adopting MTE algorithm.

If the distance of direct path (from source nodes to the attached CH) is the minimum distance, the source nodes convey its data directly through one hop to the attached cluster head. All selected CHs in the clusters transmit the aggregated data directly to the base station. In the other hand, if the distance from source nodes to the attached CHs is not the minimum distance, the source nodes forward their data through intermediate nodes in the clusters within the minimum distance. The source node transmits its data through multiple minimum hops to the cluster head. In this case, source nodes require m transmissions over a distance d and $m-1$ receptions. The energy expended in transmission and reception in each cluster in MTE mode is expressed as:

$$E_{MTE} = E_{RX-MTE} + E_{TX-MTE} = m.E_{TX} + (m-1)E_{RX} \quad (6)$$

For free space propagation:

$$E_{MTE} = m.(L.E_{elec} + \epsilon_{fs}.L.d^2) + (m-1)E_{elec}.L = L((2m-1)E_{elec} + \epsilon_{fs}.m.d^2) \quad (7)$$

For multi-path propagation:

$$E_{MTE} = m.(L.E_{elec} + \epsilon_{mp}.L.d^4) + (m-1)E_{elec}.L = L((2m-1)E_{elec} + \epsilon_{mp}.m.d^4) \quad (8)$$

In the proposed approach, transmission is occurred from member nodes to the cluster head based on MTE algorithm, from selected CH to the base station based on direct transmission. Reception of source nodes data is produced from intermediate nodes and cluster head. The total energy consumed in the proposed scheme at r rounds is expressed as:

$$E_{MTE-LEACH} = \sum_{i=0}^r (E_{MTE} + E_{CH-BS}) \quad (9)$$

The energy expended in transmission and reception in CH is expressed as:

$$E_{CH-BS} = E_{TX-Direct} + E_{RX} = L.E_{elec} + \epsilon_{amp}.d^\alpha + L.E_{elec} \quad (10)$$

Where $\alpha = 2$ and $\alpha = 4$ in free space propagation and multipath propagation, respectively.

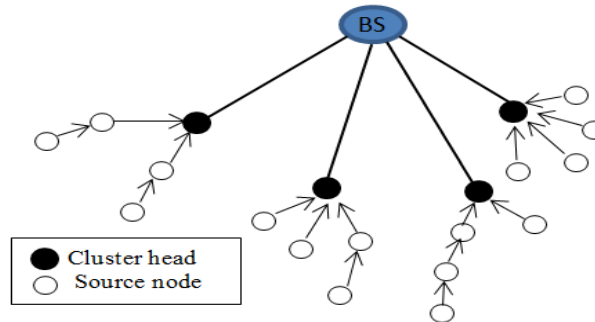


Fig. 2. Multi-hop cluster based routing architecture

In this work, we choose to employ LEACH protocol as efficient cluster-based routing approach¹³. The sensor nodes organize themselves to form clusters with a node which acts as CH to collect data from other nodes in its cluster. This role is distributed among all other sensors in order to fairly share the consumption of energy and not drain the battery of a single node²⁰. LEACH protocol consists of distributing the energy load of the network dynamically by creating organized clusters and selecting cluster heads according to a priori optimal probability²¹ (Equation 11). During the setup phase, when clusters are created, each node decides whether to become a CH or not for the current round. This decision is based on a predetermined fraction of nodes and the threshold $T(n)$, which is given by the following formula¹³:

$$T(n) = \begin{cases} \frac{P}{1 - P * (r \bmod \frac{1}{P})} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

Where P is the desired percentage of CHs, r is the current round, and G is the set of nodes that have not been elected CHs in the last $1/P$ rounds. Using this threshold, each node will be a CH at some rounds within $1/p$ rounds. After $1/p$ rounds, all nodes are once again eligible to become CHs. The nodes elect themselves to be CH in each round by choosing a random number between 0 and 1. The node becomes a cluster head for the current round if the chosen number is less than the threshold shown in (11). After those nodes elect themselves, they broadcast an advertisement to neighbor nodes. Each sensor node (Non-CH) determines to which CH will belong to, based on Received Signal Strength (RSS) of the CH advertisement message received by the node from the CH^{22, 23}. Source nodes communicate afterwards their sensed data directly with the attached cluster heads.

In the proposed approach, the network use the minimum transmission energy algorithm to form a cluster with shortest path between nodes down to their CH as shown in Figure 3. This route is calculated using Dijkstra's shortest path routing algorithm. Subsequently, nodes transmit their sensed data to the CH with multi-hop propagation. Each non-CH node has to send its data to its near successor in the path to reach his CH. Communication is the cause of the significant battery energy depletion, due to the fact that sensor node spends most of its energy in data transmission and reception. Unlike communication, data processing consumes less energy^{24, 25}. For this reason, each node receives data packet from its successor in the path, performs data fusion and compress the packet before sending it to the next node in line until it reaches the CH. When a CH receives data from all of its member nodes, it performs some necessary signal processing techniques on the data to aggregate and compress it. At this stage, the nodes collect and convey sensed data to the CH. The CH sends the received data directly towards BS.

In this approach, source nodes communicate with cluster head via multi hop routing approach instead of one direct hop in order to optimize the transmission energy consumption. The CHs collect the data from the member nodes in their respective clusters, aggregate the received data, and send it directly to the BS. The purpose of this approach is to select the optimal path from member nodes to the base station. The proposed protocol adopts a multihop communication to send the data from member nodes to the cluster heads through other intermediate nodes and directly from cluster heads to the base station. Just as LEACH protocol, multi-hop cluster based routing approach uses the same mechanism for the election of clusters-head. The protocol operates in rounds like LEACH and selects the path with minimum hops between nodes and the base station.

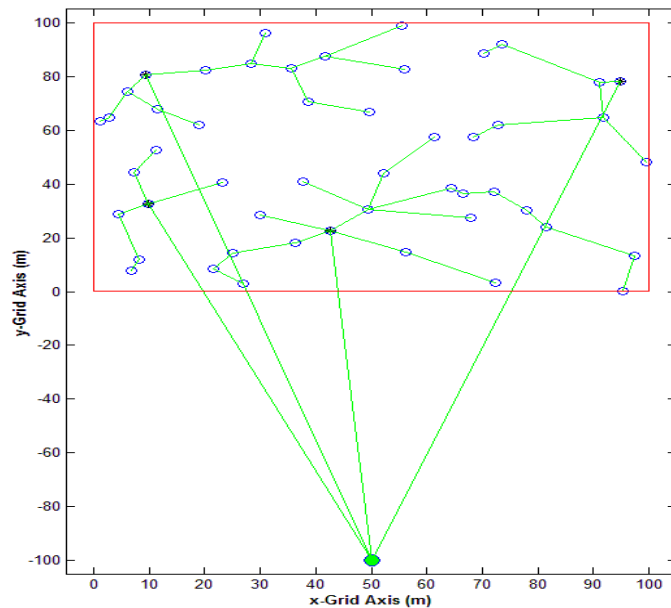


Fig. 3. Shortest paths using minimum transmission energy in cluster based routing protocol.

4. Simulation and Results

To evaluate the proposed approach and analyze its impact on the energy of the entire network, we have performed in MATLAB tool multiple simulations with various random node placements. Table 1 shows simulation parameters used in this work. A packet size of $L = 2000$ bits is used, 50 sensor nodes are randomly deployed in a network dimensions of 100m x 100m as shown in Fig.3. The base station is placed at (x=50 m, y=-100 m) and 0.05 is the probability of a node to be a cluster head in the proposed approach. All nodes begin with a starting energy level of 0.5 J. This value is commonly used in the literature since it provides small enough energy to quickly see the effect of the suggested algorithm.

Table 1. Simulation parameters.

<i>Parameters</i>	<i>Values</i>
Transmission and receiving energy	50 nJ/bit
Energy amplification for free space	10 pJ/bit/m ²
Energy amplification for multi path	0.0013 pJ/bit/m ²
Nodes initial energy	0.5 J
Data aggregation energy	5 nJ/bit/message
Packet size	2000 bits
Percentage of CH	5%
Number of nodes	50
Network size	100m x 100m
Base station position	50m x -100m

The comparison we carried-out in this work between the proposed approach, LEACH and MTE protocols is based on some key performance metrics such as: First Node Dies (FND), Half of Nodes Alive (HNA) and Last Node Dies (LND) and Energy Depletion Rate (EDR). Table II summarizes the results of these metrics (FND, HND and LND) for LEACH, MTE and our proposed approach.

Table 2. Nodes die-off statistics of the proposed approach, LEACH and MTE protocols

Protocol	Metric			
	FND	HND	LND	EDR
MTE	25	225	624	0.148
LEACH	1019	1381	1818	0.035
Proposed Approach	975	1485	2539	0.031

We evaluated the technical capability of the proposed approach vis-à-vis the metric performances. Fig. 4 displays the number of alive nodes per round of LEACH, MTE and the proposed approach. The stability period, which represents the time interval between the start of the network and the death of the first sensor node, is extended in LEACH protocol, with few more rounds than the proposed approach. The first node of the proposed approach is dead after 975 rounds, besides that the first node of LEACH is dead after 1019 rounds. However, all the sensor nodes are died after 1818 rounds for LEACH protocol, where at the same round; almost 20% of nodes are still alive in the proposed approach. Consequently, the performed sensor network using the combined multi-hop and cluster routing approach remains alive during more rounds.

Fig. 5 displays the comparison of total system energy in each round for the three approaches. The network lifespan in multi-hop cluster based routing approach is extended and lasts more than LEACH and MTE protocols. The performed approach optimizes the data routing by employing MTE protocol in each cluster. The distance between nodes is considered and free space propagation is mostly adopted, hence the minimization of inter-nodes distance result in d^2 , as the link cost parameter instead of d^4 for multi-path propagation. This propagation model transformation effectively increases the energy efficiency of the network.

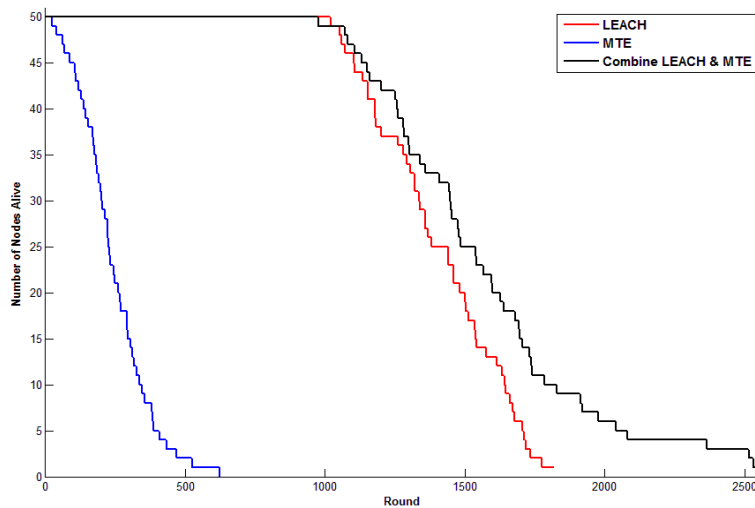


Fig. 4. Number of alive nodes per round in LEACH, MTE, and the proposed scheme.

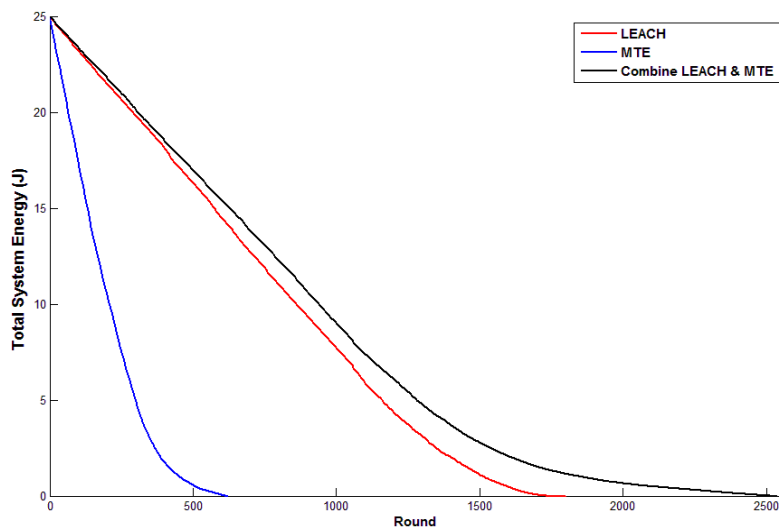


Fig. 5. Total energy of the network versus transmission rounds for LEACH, MTE and proposed scheme.

5. Conclusion

Routing algorithm is of paramount importance in optimizing energy consumption in wireless sensor network. In this paper, we proposed a multi-hop cluster based routing approach to enhance LEACH protocol by lowering the energy consumption and extending the sensor network lifetime. The performed approach is based on a combination of LEACH and MTE protocols. Results of performed simulations reveal that the proposed algorithm outperforms LEACH protocol and enables the sensor nodes to optimize transmission energy, particularly in large distances when transmission energy consumption is dominant.

The proposed hybrid approach can be practically adopted for different types of wireless sensor networks. The evolution and enhancement of the presented scheme should be done in the near future to optimize energy consumption in cluster head by considering the residual energy criteria.

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