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EETBR: Energy efficient token-based routing for wireless sensor networks

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Abstract: The most significant drawback of wireless sensor networks is energy scarcity. As there is an increasing need for operating these networks for relatively long times, energy saving becomes the key challenge in the design of the architectures and protocols for sensor networks. Therefore, several research studies have been performed for making contributions to the analysis of this energy shortage problem. Most of these research activities have been focused on finding solutions for the energy consumption of the communication unit, which is the dominant energy dissipating component of the sensor nodes. In this paper, a novel, token-based routing protocol adapted with a multitier cluster-based architecture is presented. Most of the other cluster-based schemes mainly focus on intracluster organization and communication. However, it should be mentioned that a considerable amount of energy is dissipated during the intercluster communication when compared with intracluster communication. The architecture proposed here not only deals with intracluster communication, but also considers data aggregation, multihop data transmission, and best-effort next hop selection according to a cost factor that is described for the first time in this paper. The simulation results indicate that this token-based next hop selection method together with the multitier cluster-based architecture achieves a significant amount of energy savings, which inherently yields the prolongation of the network lifetime.

Key words: Wireless sensor networks, energy efficiency, routing, clustering

1. Introduction

Today, computers and electronics have replaced manpower in various tasks that seem impossible, risky, or simply time-consuming for human beings to perform. Developments in circuits, signal processing, and other subelectronics and wireless data communication techniques have simplified the performance of these tasks and, at the same time, have made them more economical.

Wireless sensor networks (WSNs) have replaced the functions of human beings in various areas such as performing control functions in offices or factories, in the early detection of faults inside various vehicles, the prevention of forest fires, the realization of efficient agricultural watering systems, and instant notification of attacks in certain places where security is a critical issue [1–6].

WSNs cover several interdisciplinary study areas. Circuit-chip design, artificial intelligence, and wireless communication techniques intervene during the design step of the sensor nodes that are in charge of collecting, processing, and transmitting the physical data. Furthermore, a physical carrier must be conceived to carry the data and communication protocols to provide a joint agreement [2].

One of the most significant advantages of WSNs is the ability of being self-organized, or, in other words, of having an ad hoc structure. Though it is possible to use the traditional techniques of wireless ad hoc networks

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for WSNs as well, in fact, the development of techniques specific to WSNs appears to be more reasonable. Thus, several researchers have endeavored to develop communication techniques and protocols suitable for the structure and properties of WSNs [7]. One advantage is the small size of the sensor nodes, which has provided an economical method for utilizing them in various areas. However, a significant problem that has emerged is that the sensor nodes have limited resources. In this regard, the main difficulty brought by the limited power supply occurs in some situations where it is impossible to replace the energy-exhausted nodes with new ones. On the other hand, a WSN is expected to operate for months or sometimes years depending on the purpose of the application. Thus, in order to prolong the lifetime of the nodes, it is thought to generate energy from external sources such as solar energy. Nevertheless, it has been reported that the utilization of energy from external resources leads to some other issues [8,9]. Therefore, owing to the limited quantities of energy sources, there must be very efficient usage of the available energy. For this purpose, researchers are continuing their works on communication techniques that lead to less energy consumption.

It has been revealed that sensor nodes consume considerably more energy during data transmission compared to data processing [10]. Moreover, it is observed that the amount of energy consumed during the transmission of a single bit between 2 wireless sensor nodes is almost equal to the amount of energy consumed by a sensor node performing 1000 transactions [11].

In this paper, a multitier cluster-based architecture is proposed with a novel token-based routing protocol that aims to provide fair load distribution among the nodes. While other methods, such as low-energy adaptive clustering hierarchy (LEACH) [12,13], the brainchild of clustering, and its followers, hybrid energy-efficient distributed clustering (HEED) [14] and power-efficient gathering in sensor information systems (PEGASIS) [15], dealt only with intracluster communication, this research deals with the more energy-consuming challenge involving intercluster communication. A token-based, localized, energy-aware next hop selection idea is proposed, which provides a fair load balancing and fair order of the next hop selection between adjacent clusters residing in the same layer. As discussed in [16,17], employing multiple sinks in WSNs provides significant gains in terms of the fair load distribution and lifetime prolongation for the nodes located in the hot-spot region. In addition, the multitier approach is applied in cooperation with the multiple sinks idea. With the aim of alleviating the burden of the nodes located in the so-called hot-spot region, the network structure is divided into multiple nested layers. The number of nodes that each cluster contains is found to vary depending on the layer in which the cluster is located. As the workload of nearby nodes is higher than that of those further away, the clusters located near the sinks contain more nodes when compared to the ones located in the inner layers.

This paper is organized as follows. In Section 2, several studies about energy conservation with clustering in WSNs are reviewed. In Section 3, a new routing mechanism with a token-based route selection process is proposed. Finally, the simulation results are compared for various routing criteria in Section 4, and the conclusion is provided in Section 5.

2. Related work

LEACH [12,13] is an energy-efficient clustering-based protocol that has created a base for several research activities. The topology is split into clusters, with each containing a variable number of sensor nodes. Each node belongs to a single cluster with a cluster head (CH) that is randomly chosen at the beginning of each round. Plain nodes are only obliged to pass on the data that they gathered from the environment to their CHs. By the time the CHs retrieve all of the packets from the plain nodes in their clusters, they compress and reduce the size of the data to be sent to the sink.

Data compression can be performed by applying either data fusion or data aggregation. The performance of the energy savings achieved by the data aggregation method was examined in [18–20]. The data fusion method is another data compression technique. Data fusion is an application-specific method that applies signal processing methods to combine different signals gathered from various sources, thereby extracting the appropriate data from the noise and forming more accurate data to be sent toward the sink [12].

PEGASIS [15] is an improvement over LEACH. However, it should be mentioned that in PEGASIS, a chain structure is applied rather than a clustering scheme.

HEED [14] is another energy-efficient approach for clustering nodes in sensor networks. In this method, CHs are selected periodically, but not at each round. The CH selection process is made according to the hybrid residual energy levels of the nodes and a parameter called the average minimum reachability power (AMRP). The AMRP of a node is defined as the assumed total energy consumed by all of the nodes in the cluster during intracluster communication when this node becomes the CH.

In another cluster-based approach [21], the network was characterized by a 2-level hierarchical network architecture. The first level consists of clusters called aggregated units (AUs) and the second level consists of a backbone generated by relaying nodes for performing multihop forwarding between clusters and the sink. Primarily, data are collected by the common nodes in the first-level network and directed to the CH in a time division multiple access (TDMA) manner, similar to the method in LEACH. The CHs are charged with aggregating the data collected and transmitting to the relay nodes (RNs) periodically. The RN in an AU is responsible for taking data from the CH and relaying them to the other RNs on the way to the sink.

Another idea that has been proposed for clustering was energy-aware routing in cluster-based sensor networks [22]. In that research, there is a single command node that configures the clusters in the network. In each cluster, there is a single nonenergy-constrained node that is charged to be the gateway node. Similar to LEACH, all communication occurs between the plain nodes and the gateway node. The gateway nodes collect the intracluster data and send the fused data directly to the command node.

The architecture proposed in [23] was constructed over the ZigBee/802.15.4 protocol [24]. The tree structure of the clusters is assumed to be created using the tree addressing scheme of ZigBee. The main purpose of the study was to design a schedule that regulates the sleep/wakeup schedules of the clusters concurrently by preventing intercluster collisions.

In addition to the aforementioned studies, researchers are still making attempts to develop different clustering schemes [25–27] and many of them have constructed their architectures based on the structure described in LEACH. A sample cluster generation and setup scheme was defined in [28]. In that research, once all of the nodes are settled over the topology, a clustering mechanism starts to work iteratively from the sink to the edge nodes of the network, until none of the nodes in the network remain unclusterized.

3. Architecture

In this study, the cluster formation and notification of the sensor nodes is done according to the method proposed in [28] at the setup stage, which is outside of the scope of this paper. Sensor nodes are assumed to identify their own geographical positions as well as their neighbor nodes in the cluster they locate by means of a GPS device or the broadcast of a preannouncement by the sinks. As indicated above, in order to achieve a fair load distribution, multiple sinks are placed around the perimeter of the network area.

3.1. Intracluster communication

Based on the idea applied by LEACH, there is a single CH in each cluster, which is renewed at the beginning of each round. However, it should be mentioned that there are some differences regarding the intracommunication scheme of LEACH. In LEACH, a frame is described in the time domain and this frame is divided into small subframes that are each reserved for the use of a sensor node. Every node transmits its in-node processed data to its CH in its preallocated subframe, which indicates an obvious application of time division multiplexing. In this approach, the code division multiple access (CDMA) scheme is applied for intracluster communication, as it is used in cellular technology. As far as it is known, none of the cluster-based works have applied CDMA for intracellular communication. In fact, almost all of them apply TDMA or a randomized channel access scheme such as carrier sense multiple access with collision avoidance. In the method proposed here, during the cluster's setup phase, every node in each cluster is assigned its own code that is orthogonal with the codes of the other nodes in that cluster. The purpose of using CDMA in this architecture is to achieve a capacity increase that cannot be neglected, as well as to avoid potential retransmission energy consumptions stemming from multiple access errors. Gilhousen et al. in their research and experiments examined the capacity gains of CDMA among other multiple access schemes [29], and they mentioned that frequency modulation based on frequency division multiple access (FM/FDMA) supports only 60 users in a cell in which a 12-MHz band is employed. However, by employing CDMA, 108 users could be supported using only 10% of the band employed in FM/FDMA. In a situation where the TDMA scheme is used for intracellular communication, the capacity increases almost 3-fold compared to that of FM/FDMA. However, the performance of TDMA remains with a factor of 6 below the performance of the CDMA scheme.

For intracell communication, every cluster uses the frequency specifically assigned to it at the setup stage permanently. Similar to cellular technology, the frequency-reusing approach is utilized. The CH of each cluster transmits its intracluster data to the CH of a cluster located at the outer layer through the channel used for intracluster communication. Thus, the transmitter CH assigns its transmitter radio to the receiver channel of the next hop CH. As a result, every node in the topology owns 2 radios. One of the radios is assigned for the intracluster and intercluster transmitting operations, while the other is devoted to receiving incoming packets from inner layers.

The structure of an intracluster packet is presented in Figure 1.

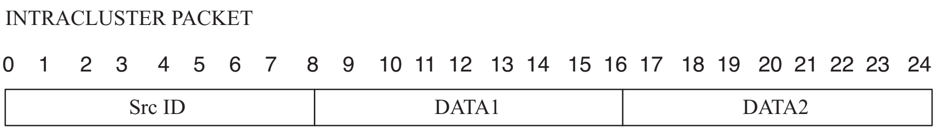

Figure 1. Intracluster packet structure.

Sensor nodes put their identifications (IDs) into a packet that is unique inside the cluster but is reusable outside of the cluster. In order to make the ID unique, the geographical coordinates of the nodes are determined. In the architecture proposed here, clusters are constrained to contain a number of nodes so as to not exceed a maximum value that can be represented with 8 bits. Thus, 1 byte is sufficient for identifying each cluster individually in a cluster. Data1 and Data2 are the physical data measured by the sensor nodes. In this study, application-specific values such as temperature and humidity are measured.

By the time the packet is generated, plain nodes encode their packets using the orthogonal code assigned at the setup stage by the controller. Each node is aware of the codes of the other nodes in its cluster. Hence, when a sensor node is elected as the CH, it is already equipped for decoding the incoming signal and extracting the original signal of each node. Subsequent to sending their data to the CH, plain nodes do not need to remain in an active state owing to the fact that all communication after this stage would be carried on by the CHs. Thus, until the startup of the next round, which is the next data collection period, plain nodes remain in a sleep state and do not unnecessarily consume energy.

In order to maintain the load balance and fairness, in each round, a different node among the active ones with a satisfying residual energy level is charged as the CH in a round-robin manner. As clusters located near the sinks contain more nodes, nodes located inside these larger clusters become CHs less frequently than the ones located in inner layer clusters.

The CH applies data aggregation after decoding the data arriving from the plain nodes in the cluster. Furthermore, instead of sending the data of every node, the minimum and maximum values are selected and sent with the owner IDs of these packets.

3.2. Energy efficient token-based routing (EETBR) selection depending on the cost factor

3.2.1. Next hop calculation

Multiple sinks are settled around the network area owing to the fact that when setting a network with a single sink located on one side of the topology, all of the data traffic from the nodes flows over the nodes located at the same side as the sink, and the energy of those nodes located around the sink quickly depletes. Hence, CHs have the opportunity to select the most convenient sink and forward their data to that sink.

In the architecture proposed here, the nodes intend to forward their data to the closest sink deployed around the topology. The closest sink is defined, and then the next step is the determination of the next hop CH. Each node stores a table called the ResidualEnergyTable that contains information about the residual energy levels of the neighbor nodes in the cluster. Thus, at the beginning of the next hop determination process, the nodes first check their ResidualEnergyTables and calculate the CostFactor parameter for each record. The calculation is performed according to Eq. (1):

$$\text{CostFactor} = (RsdEngCH_i)^{-1} \times d^{\text{exp}}, \tag{1}$$

where RsdEngChi and d denote the residual energy level of the candidate next hop CH and the distance between the transmitter and the candidate next hop CH, respectively. The CH with the minimum cost value toward the sink and located in the next layer is selected as the next hop. The value of exp is defined after various simulations. As can be clearly seen in Figure 2, the optimum value of exp is defined as 3, which is applied during the simulations.

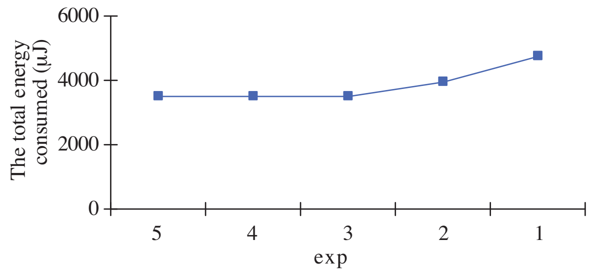

Figure 2. Total energy dissipation in the network depending on the value of exp.

3.2.2. Token mechanism

Another challenge to be considered during the next hop selection stage is that the CHs of the 2 clusters that are adjacently located at the same layer can concurrently select the same next CH. Therefore, though it is possible to select 2 distinct CHs as the next hop, without applying any control mechanism, 2 CHs could select the same CH as their next hop. As a result, load balance and fairness might not be achieved.

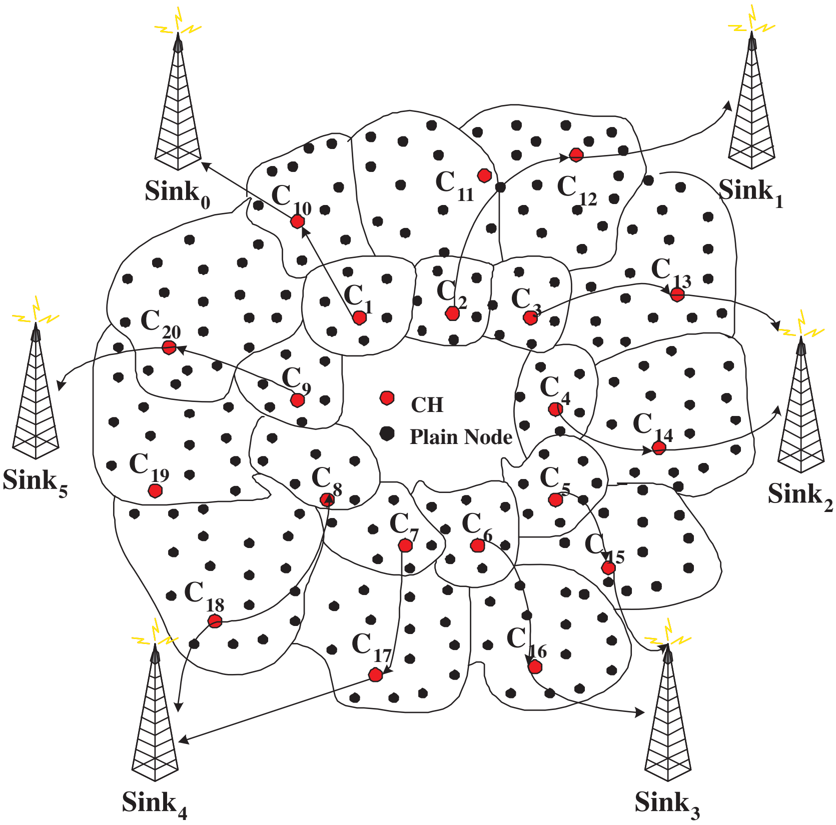

Figure 3. Sample scenario on a multitier cluster-based topology.

A token mechanism is included in order to keep the next hop selection crash under control. For the first round, the CH of the cluster with the smallest ID number, that is, C1 in Figure 3, is given the opportunity to first select its next hop. According to the routing method and the cost factor given in Eq. (2), CH_{10} is selected as the next hop. Subsequent to calculating and defining the next hop as CH_{10}, CH_1 creates a token. It then includes the ID of CH_{10} into the token and passes it to CH_2 and CH_9. By the time CH_2 and CH_9 receive the token, they start calculating and defining next hop CHs with IDs that do not appear in the list stored in the token. As CH_{10} is already chosen by CH_1, CH_2 must select either CH_{11} or CH_{12} as the next hop CH. Taking into account the token and the cost factor, CH_2 elects CH_{12} as the next hop. The next hop definition procedure continues until the tokens arrive at CH_5 and CH_6. After these CHs define their next hops, they pass the token on to their neighbors. Though CH_5 and CH_6 will receive the same tokens again, by checking out the round number and the sequence number fields, they will discard the duplicate tokens. Thus, while selecting a next hop, the criterion is to find the minimum cost value that is not selected by the other CHs located in the same layer. However, there emerges another issue to be considered: if in every round the same CH is given the opportunity to first define the next hop, how can fairness be achieved? The solution suggested here is to give the first opportunity of the next hop selection to the CHs in a round robin manner; that is, when a CH is the first for the present round, it is the last for the next one. The token structure is illustrated in Figure 4.

TOKEN STRUCTURE

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

SrcID	Round Number
SequenceNumber	SelectedNextHopClusterID

Figure 4. Token structure.

Figure 5 illustrates the algorithmic representation of our routing method operated by a CH.

```
Sink sink ← CalculateClosestSink()
minCostFactor ←1000
if (this.id == ( roundNumber- ((roundNumber / this.Cluster. numOfNodes)* this.Cluster. numOfNodes))) then //getting the
next hop selection opportunity first
   for i ← 1 to sizeOf (ResidualEnergyTable) do
        d = ResidualEnergyTable[i].distance
        costFactor = exp(ResidualEnergyTable[i]. ResidualEnergyLeve,-1) * exp(d,3)
        if (costFactor < minCostFactor) then
              minCostFactor ← costFactor
              nextHop ← ResidualEnergyTable[i].nodeID
        end if
   end for
  Token token ← CreateToken(nextHop)
  PassTokenToAdjacentCHs(token)
else
  Token token ← getToken()
  If (tokenAlreadyReceived == false) then
   for i ← 1 to sizeOf (ResidualEnergyTable) do
     d = ResidualEnergyTable[i].distance
     costFactor = exp(ResidualEnergyTable[i]. ResidualEnergyLeve,-1) * exp(d,3)
     if (costFactor< minCostFactor)&&(token.IDList.Contains(ResidualEnergyTable[i].nodeID)== false)) then
            minCostFactor ← costFactor
            nextHop ← ResidualEnergyTable[i].nodeID
     end if
   end for
   token.IDList.add(nextHop)
   PassTokenToAdjacentCHs(token)
  else
    Discard(token)
  end if
end if
```

Figure 5. Energy efficient token-based routing (EETBR) algorithm.

3.3. Intercluster communication

Intercluster packets differ from each other owing to the layer number in which the owner cluster is located; that is, a packet that originates in a cluster located in layer 1 does not have the same structure and size as a packet that originates in a cluster located in layer 2. Packet structures are represented and briefly described below.

As clarified in Figure 6, the IDs of all of the hops that the packet passes through in each layer appear in the packet. This is necessary in order to inform the sinks about the remaining energy levels of each node in the network. The sinks calculate the amount of energy dissipated by the nodes through which the packet passes and the attendant sink announces this information throughout the network during the broadcast stage. Every node that receives this broadcast message updates the related records of the ResidualEnergyTables. This table is admitted during the next hop selection process with the aim of providing load balance. Finally, fields denoted by Data x.x are the maximum and minimum values measured in the cluster. The packet structures emerging from clusters located in layers 2 and 3 are shown in Figures 7 and 8, respectively.

INTERCLUSTER PACKET TYPE ORG FROM LAYER 1

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

3. ClsID	3. ClsCHID	2. ClsID
2. ClsCHID	Src ClsID	Src ClsCHID
Src1 ID	Src2 ID	Data 1.1
Data 1.2	Data 2.1	Data 2.2

Figure 6. Interpacket structure originating from the first tier.

INTERCLUSTER PACKET TYPE ORG FROM LAYER 2

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

3. ClsID	3. ClsCHID	Src ClsID
Src ClsCHID	Src1 ID	Src2 ID
Data 1.1	Data 1.2	Data 2.1
Data 2.2		

Figure 7. Interpacket structure originating from the second tier.

INTERCLUSTER PACKET TYPE ORG FROM LAYER 3

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Src ClsID	Src ClsCHID	Src1 ID
Src2 ID	Data 1.1	Data 1.2
Data 2.1	Data 2.2	

Figure 8. Interpacket structure originating from the third tier.

As a packet originating from the third layer is directly transmitted to a sink, there is no requirement for a record to maintain the next hop information in the packet.

3.4. Residual energy changes notification

All of the sinks are familiar with the geographical position of each node in the topology. Therefore, they can calculate the energy consumed during send and receive operations by the nodes on the complete path by looking at the related fields of the packets.

The amount of energy consumed by the sensor nodes differs depending on their states, i.e. depending on whether they are a CH or a plain node in their clusters. CHs are known to consume considerably more energy than plain nodes. For event-based applications, sensor nodes do not transmit all of the data that they gather from the environment. As mentioned earlier, in-node processing is applied in the architecture that has been proposed here. Therefore, there is probability $1/p_o$ for the occurrence of an event, and the probability of the nonoccurrence of an event is represented by $p_{non} = 1 - (1/p_o)$. Thus, these probabilities must be considered while calculating the energy dissipated by the nodes.

The total energy consumed by CH N located in cluster C in layer L is given by Eq. (2):

$$E_{Total} = E_{snd} + E_{rcv}, \tag{2}$$

where E_{snd} and E_{rcv} denote the energy dissipated while sending and receiving data, respectively. In the literature, the energy dissipated during data transmission is calculated according to Eqs. (3)–(8).

$$E_{snd}(l,d) = E_{snd-elec}(l) + E_{snd-amp}(l,d) \tag{3}$$

$$E_{snd}(l,d) = (l \times E_{elec}) + (l \times \varepsilon_{fs} \times d^2), \quad d < d_o \tag{4}$$

$$(l \times E_{elec}) + (l \times \varepsilon_{mp} \times d^4), \quad d \geq d_o \tag{5}$$

$$E_{rcv} = l \times E_{elec} \tag{6}$$

Here, l denotes the number of bits transmitted and d represents the Euclidean distance between the nodes. As is already known, if the distance between 2 nodes is below the threshold distance that is denoted by d_o, the energy dissipated by the sender node is calculated according to the first part of Eq. (4). Otherwise, the energy consumed by the sender node is calculated according to the second part. It is then obvious that if the distance between 2 nodes increases, the amount of energy consumed increases exponentially.

A CH is responsible for transmitting data from its own cluster, as well as the incoming data of the clusters located in the inner layers. Thus, a CH consumes energy at both times, when transmitting data from its own cluster as well as when relaying the incoming data from the inner clusters. The amount of energy consumed by a CH when sending data from its own cluster is represented by $E_{sndIntClsDt}$ in Eq. (6). The amount of energy dissipated by a CH while relaying the incoming data of the clusters located in the inner layers is denoted by $E_{sndIntDtInLay}$. As identified above, during the next hop selection phase, each CH in the same layer has to specify its choice in the token and pass it to its adjacent neighbors. During this token transmission, the amount of energy consumed is represented as E_{sndTkn}.

$$E_{snd} = E_{sndIntClsDt} + E_{sndInterDtInLay} + E_{sndTkn} \tag{7}$$

In addition, a CH not only consumes energy during the send operation, but also dissipates energy while receiving data. The amount of energy consumed by a CH during the data receiving process is calculated according to Eq. (7).

$$E_{rcv} = E_{rcvIntraClsDt} + E_{rcvInterDt} + E_{rcvTkn} + E_{rcvNot} \tag{8}$$

During the intracluster communication stage, a CH consumes energy while receiving the data arriving from the plain nodes located in its cluster, which is denoted by $E_{rcvIntraClsDt}$. The energy consumed while receiving the incoming data of the clusters located in the inner layers is represented as $E_{rcvInterDt}$. The energy consumed while receiving the token from the CH of the adjacent cluster is denoted by E_{rcvTkn}. Subsequent to the completion of the data transmission stage, which means that all of the data from all of the clusters arrive at the sinks, the attendant sink sends a notification message to the entire topology. During this notification stage, a CH also consumes energy while receiving the notification message sent by the sink, which is represented as E_{rcvNot} in Eq. (7).

On the contrary, plain nodes consume energy only during intracluster communication, depending on the event occurrence probability given by Eq. (8).

$$E_{sndIntraClsDtToCH}(P) = E_{snd}(l, d_{CH}) \times (1/p_o(P)) \tag{9}$$

Each time a packet arrives at the sink, the sink records the energy changes of the nodes on the path. Packets that emerge from different clusters arrive at different sinks. Thus, every sink must inform the other sinks about the incoming packets. A notification mechanism between the sinks is utilized to achieve this informing process. A sink is charged permanently with the task of informing all of the nodes in the topology about the changes occurring in the residual energy levels. Thus, all of the other sinks convey the data they receive to that responsible sink. At the beginning of each round, every sink starts a timer. When the timer expires, all of the sinks transmit their data to the sink charged with the notification process. In order to prevent collisions, the CDMA mechanism is employed here. Each sink is assigned its own code that is orthogonal to the codes of the other sinks. Thus, all of the other sinks can send information about incoming packets to the informer sink at the same time without a collision. As soon as the informer sink receives the messages from the other sinks, it decodes the messages and then generates the ultimate message and broadcasts it to the entire network. The structure of the notification message is depicted in Figure 9.

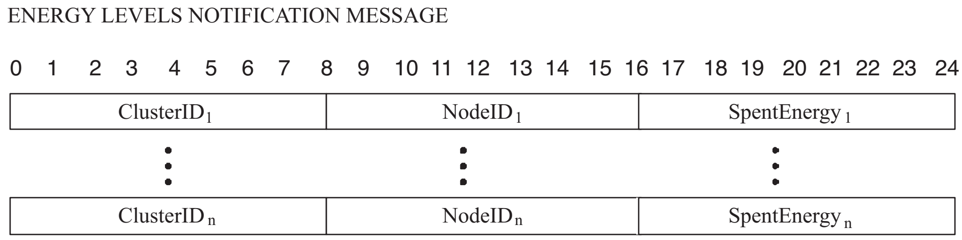

Figure 9. Notification message structure.

4. Experiments

4.1. Simulation setup

To evaluate the performance of the proposed architecture, simulations are conducted on a multilayered topology. For the sake of experimental simplicity, each layer contains clusters that are uniformly sized and located. It should be noted that cluster formation is beyond the scope of this paper. Each node is assumed to own 2 radios. One of the radios is assigned to intracluster and intercluster sending operations, while the other is devoted to receiving incoming packets from the inner layers. As illustrated in the Table, the bit rate of the radios is set to 30 kbps. Following the values defined for the parameters E_{elec}, ε_{fs}, and ε_{mp} in the literature, the values given in the Table are used during the energy consumption calculations. The network structure on which the simulations are performed is composed of 3 layers. For the sake of simplicity, each layer is divided into 4 $\times$ n clusters, where n denotes the layer number. In this architecture, layers 1, 2, and 3 contain 4, 8, and 12 clusters, respectively. Each cluster is assumed to have a circular shape with a radius of $R_0 \times n$. R_0 is the radius of a cluster located in the innermost layer and is set to 16 m. Thus, a cluster in the second layer has a radius of 32 m. Again for the sake of simplicity, every cluster in the same layer contains the same number of sensor nodes. The number of sensor nodes located in a cluster at the nth layer is defined as $(n^2 + n + 4)/2$. Thus, a cluster located in the third layer contains 8 sensor nodes, and a total of 148 nodes are deployed in the network. The lifecycle comprises periodical rounds, each taking 18.5 ms.

4.2. Simulation results

Simulations are performed for 100 rounds, with each taking 18,500 μs. As the first step, the performance of the next hop selection criteria, depending on the cost factor regarding 2 other next hop selection methods, is discussed. In the approach proposed here, the CHs intend to forward their data toward the closest sink in the network in order to consume minimum energy. Hence, next hops must be selected among the nodes on the way to the closest sink. The next hop selection criterion to be compared is the selection of the next CH that is closest to the sink. This idea is also known as greedy perimeter stateless routing (GPSR) [30]. The second method is the selection of the next CH that is closest to the transmitter CH. This method is represented by NHCTS in the Figures. As clearly depicted in Figures 10–12, the other 2 methods approximately show the same performance. However, the cost factor criterion here prolongs the lifetime of the network, as depicted in Figure 13. After 60 rounds, there are no live nodes in the network when using the GPSR and NHCTS routing methods. On the other hand, there are live nodes even after 70 rounds when the proposed EETBR method is employed.

Table. Simulation parameters.

Radio transmission rate	30 kbps
d_0	30 m
R_0	16 m
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
Em_p	0.0013 pJ/bit/m^4
Number of layers	3
Number of nodes in the network	148
Number of clusters in the nth layer	$4 \times n$
Number of nodes in each cluster in the nth layer	$(n^2 + n + 1)/2$
Duration of a round	18.5 ms

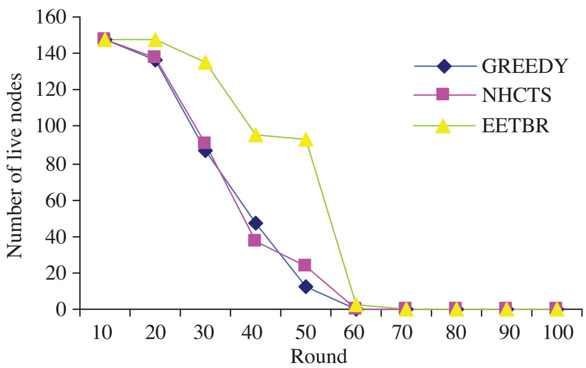

Figure 10. Number of live nodes remaining in the network after various rounds.

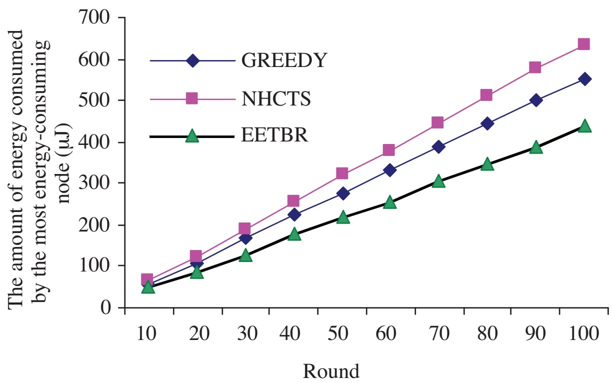

Figure 11. The amount of energy dissipated by the most energy-consuming node.

The lifetime of the network ends with the energy depletion of the first node in the network. As nodes consume less energy with the EETBR scheme, the lifetime of the network is inherently prolonged, as shown in Figure 13.

The amount of energy dissipated by the nodes during data transmission is exponentially proportional to the distance between the sender and the receiver. Hence, in this architecture, the nodes intend to direct their data to the closest sink among the sinks surrounding the topology. Furthermore, instead of a CH sending its data directly to the sink, relaying to an intermediate CH located in the direction of that sink is an effective idea for achieving lowered energy consumption. If CHs send the data aggregated in their clusters directly to the sink, as is done in LEACH, after 30 rounds, all of the nodes in the network are depleted of energy, as shown in Figure 14. However, with multihop transmission as applied in the proposed approach, the CHs relay their aggregated data to a next hop CH located in the outer layer. Thus, the nodes dissipate less energy and the lifetime of the network is prolonged inevitably, as illustrated in Figure 15.

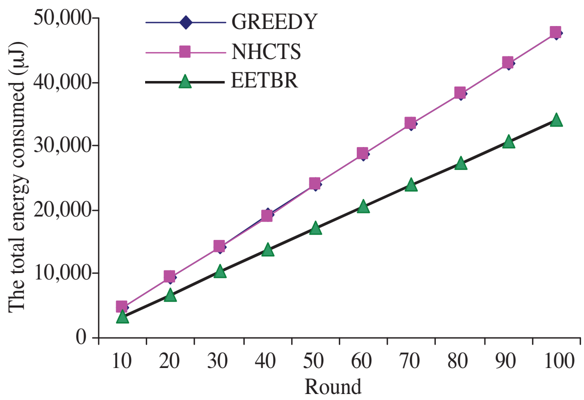

Figure 12. Total energy consumed in the network.

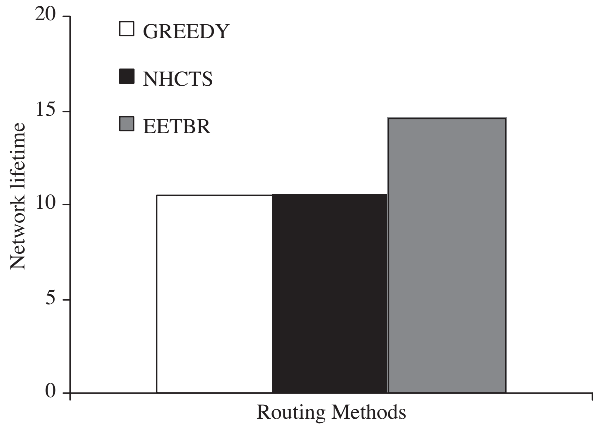

Figure 13. Network lifetime.

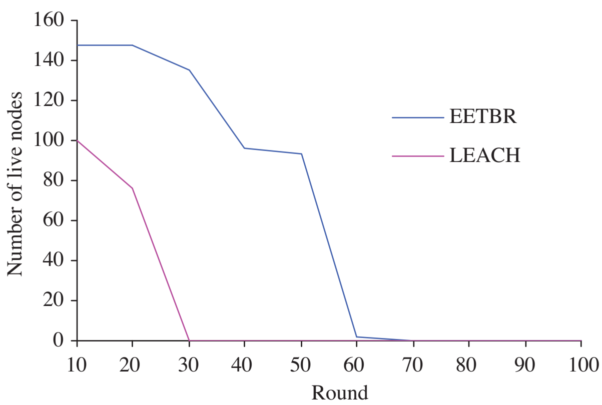

Figure 14. Number of live nodes in the network.

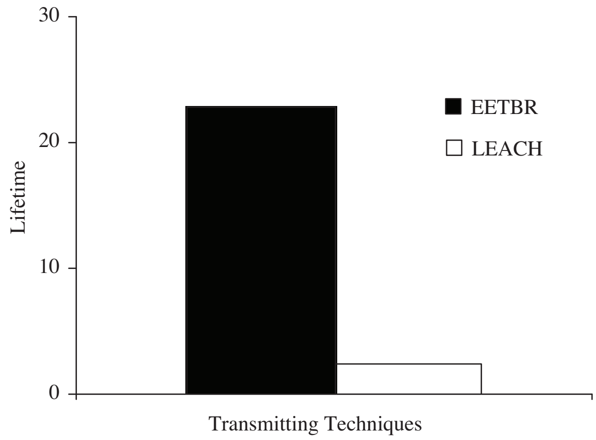

Figure 15. Network lifetime.

5. Conclusion

In this paper, an energy-efficient cluster-based architecture is presented that contains various energy-efficient techniques with a novel token-based route selection method. In order to achieve fair load distribution, and thereby network lifetime prolongation, next hop selection is done according to a cost factor. Cluster-based structures have proven to be more energy efficient with respect to other structures; this fact is observed in the simulations with brief measurements. As discussed in the previous sections, a hot-spot problem emerges in wireless sensor networks owing to the fact that sensor nodes located near the sink must also relay data from other sensor nodes that are located further from the sink, as those further nodes do not have the opportunity to transmit their data directly to the sink. Thus, a multitier structure is employed with a clustering mechanism.

In this architecture, clusters located close to the sinks are sized larger and contain more nodes than the ones further from the sink. This is because nodes in the nearby clusters transmit more data and there is lesser probability of being the CH in order to prevent energy depletion.

Another concept that helps in improving the energy efficiency is that of multiple sinks. By setting a network to a single sink located on one side of the topology, all of the data traffic from the nodes flows over the nodes located on the same side of the sink. Hence, those nodes are quickly depleted of energy and the network lifetime reduces. However, by employing multiple sinks surrounding all of the topology, nodes can forward their data to the most convenient sink.

Furthermore, another challenge discussed in this study is to determine a cost factor that could be applied during the next hop selection process. The cost factor proposed in the architecture helps nodes to select the optimum next hop node by means of the residual energy level of the next node and the distance between the sender–receiver pair. By employing the cost factor-considering routing method, the network lifetime is prolonged by a factor of 50%.

Future work will be aimed at improving the proposed architecture to accompany multimedia sensor networks.

References

[1] K. Sohraby, D. Minoli, T. Znati, Wireless Sensor Networks, New York, Wiley, 2007.

[2] K. Whitehouse, "The design of calamari: an ad-hoc localization system for sensor networks", MSc, University of California at Berkeley, 2002.

[3] K. Whitehouse, F. Jiang, A. Woo, C. Karlof, D. Culler, "Sensor field localization: a deployment and empirical analysis", Technical Report, University of California at Berkeley, 2004.

[4] K. Whitehouse, C. Sharp, E. Brewer, D. Culler, "Hood: a neighborhood abstraction for sensor networks", Proceedings of the 2nd ACM International Conference on Mobile Systems, Applications, and Services, pp. 99–110, 2004.

[5] K. Whitehouse, C. Karlof, D. Culler, "Getting ad-hoc signal strength localization to work", Technical Report, University of California at Berkeley, 2004.

[6] W.S. Conner, J. Heidemann, L. Krishnamurthy, X. Wang, M. Yarvis, "Workplace applications of sensor networks", In: N. Bulusu, S. Jha, Eds., Wireless Sensor Networks: A Systems Perspective, London, Artech House, pp. 289–307, 2004.

[7] F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, "A survey on sensor networks", IEEE Communications Magazine, Vol. 40, pp. 102–114, 2002.

[8] G. Anastasi, M. Conti, M.D. Francesco, A. Passarella, "Energy conservation in wireless sensor networks: a survey", Ad Hoc Networks, Vol. 7, pp. 537–568, 2009.

[9] R. Want, K.I. Farkas, C. Narayanaswami, "Energy harvesting and conservation", IEEE Pervasive Computing, Vol. 4, pp. 14–17, 2005.

[10] V. Raghunathan, C. Schurgers, S.I. Park, M.B. Srivastava, "Energy-aware wireless microsensor networks", IEEE Signal Processing Magazine, Vol. 19, pp. 40–50, 2002.

[11] G.J. Pottie, W.J. Kaiser, "Wireless integrated network sensors", Communications of the ACM, Vol. 43, pp. 51–58, 2000.

[12] W.R. Heinzelman, A. Chandrakasan, H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks", Proceedings of the 33rd Hawaii International Conference on System Sciences, 2000.

[13] W. Heinzelman, A. Chandrakasan, H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks", IEEE Transactions on Wireless Communications, Vol. 1, pp. 660–670, 2002.

[14] O. Younis, S. Fahmy, "HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks", IEEE Transactions on Mobile Computing, Vol. 3, pp. 366–379, 2004.

[15] S. Lindsey, C.S. Raghavendra, "PEGASIS: power-efficient gathering in sensor information systems", IEEE Aerospace Conference Proceedings, Vol. 3, pp. 1125–1130, 2002.

[16] T. Çevik, A.H. Zaim, D. Yıltaş, "Localized power aware routing with an energy efficient pipelined wakeup schedule for wireless sensor networks", Turkish Journal of Electrical Engineering & Computer Sciences, Vol. 20, pp. 964–978, 2012.

[17] W. Yu, S.S. Wei, B.J. Shie, "Activating the hot spot problem by switching multiple sinks in wireless sensor networks", Proceedings of the 5th International Conference on Mobile Ad-hoc and Sensor Networks, pp. 204–211, 2009.

[18] B. Krishnamachari, D. Estrin, S. Wicker, "Modelling data-centric routing in wireless sensor networks", Proceedings of the 21st Annual Joint Conference of the IEEE Computer and Communications Societies, 2002.

[19] J. Heidemann, F. Silva, C. Intanagonwiwat, R. Govindan, D. Estrin, D. Ganesan, "Building efficient wireless sensor networks with low-level naming", Proceedings of the 18th ACM Symposium on Operating Systems Principles, Vol. 35, pp. 146–159, 2001.

[20] C. Intanagonwiwat, R. Govindan, D. Estrin, "Directed diffusion: a scalable and robust communication paradigm for sensor networks", Proceedings of the 33rd International Conference on System Sciences, 2000.

[21] E. Toscano, L.L. Bello, "A topology management protocol with bounded delay for wireless sensor networks", Proceedings of the IEEE Emerging Technologies and Factory Automation Conference, pp. 942–951, 2008.

[22] M. Younis, M. Youssef, K. Arisha, "Energy-aware routing in cluster-based sensor networks", Proceedings of the IEEE International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems, pp. 129–136, 2002.

[23] Z. Hanzalek, P. Jurcik, "Energy efficient scheduling for cluster-tree wireless sensor networks with time-bounded data flows: application to IEEE 802.15.4/ZigBee", IEEE Transactions on Industrial Informatics, Vol. 3, pp. 438–450, 2010.

[24] IEEE, IEEE P802.15 Wireless Personal Area Networks: Proposal for Factory Automation, Working Draft Proposed Standard, 2009.

[25] S. Banerjee, S. Khuller, "A clustering scheme for hierarchical control in multi-hop wireless networks", Proceedings of the 20th Annual Joint Conference of the IEEE Computer and Communications Societies, Vol. 2, pp. 1028–1037, 2001.

[26] R. Krishnan, D. Starobinski, "Efficient clustering algorithms for self-organizing wireless sensor networks", Ad Hoc Networks, Vol. 4, pp. 36–59, 2006.

[27] A.A. Abbasi, M. Younis, "A survey on clustering algorithms for wireless sensor networks", Computer Communications, Vol. 30, pp. 2826–2841, 2007.

[28] Ö. Sağlam, M.E. Dalkiliç, "A self organizing multihop clustering protocol for wireless sensor networks", Proceedings of the 5th International Conference on Mobile Ad-hoc and Sensor Networks, pp. 33–40, 2009.

[29] K.S. Gilhousen, I.M. Jacobs, R. Padovani, A.J. Viterbi, L.A. Weaver, C.E. Wheatley, "On the capacity of a cellular CDMA system", IEEE Transactions on Vehicular Technology, Vol. 40, pp. 303–312, 1991.

[30] B. Karp, H.T. Kung, "GPSR: Greedy perimeter stateless routing for wireless networks", Proceedings of the Annual International Conference on Mobile Computing and Networking, pp. 243–254, 2000.