

Cluster-based Routing Protocols for Energy Efficiency in Wireless Sensor Networks

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1. Introduction

Thanks to recent advances in micro-electronics and wireless communications, wireless sensor networks (WSN) are foreseen to become ubiquitous in our daily life and they have already been a hot research area. A WSN is made of large number of low cost sensor nodes with processing and communication capabilities. While sensors are small devices with limited power supply, a WSN should operate autonomously for long periods of time in most applications. In order to better manage energy consumption and increase the whole network lifetime, suitable solutions are required at all layers of the networking protocol stack. In particular, energy-aware routing protocols at the network layer have received a great deal of attention since it is well established that wireless communication is the major source of energy consumption in WSN.

The network layer in WSN is responsible for delivery of packets and implements an addressing scheme to accomplish this. It mainly establishes paths for data transfer through the network. Compared to traditional ad-hoc networks, routing is more challenging in wireless sensor networks due to their limited resources in terms of available energy, processing capability and communication, which are major constraints to all sensor networks applications. These constraints yield frequent topology changes making route maintenance to be a non-easy task. Additionally, the typical mode of communication is many-to-one, from multiple sources to a particular sink rather than from one entity to another. Finally, since data related to one phenomena may be collected by multiple sensors, a significant redundancy is likely to be present and has to be considered. This is why routing protocols proposed for ad-hoc networks in recent years are not suitable for wireless sensor networks. Alternative approaches that take the above limitations into account with energy-awareness are required. Due to that, multiple routing protocols for WSN have been proposed (Akkaya & Younis, 2005; Al-Karaki & Kamal, 2004).

From network organization perspective, routing protocols can coarsely be classified in two main classes : flat network routing and hierarchical network routing. In a flat topology, each node plays the same role and has the same functionality as other sensor nodes in the network. When a node needs to send data, a flat routing protocol attempt to find a route to the sink hop by hop using some form of flooding. The most popular flat-based routing in WSN are data-centric protocols like SPIN (Heinzelman et al., 1999) and Directed Diffusion (DD) (Intanagonwiwat et al., 2003). Data-centric routing protocols were shown to save energy through in-network data aggregation. In order to limit energy consumption due to un-

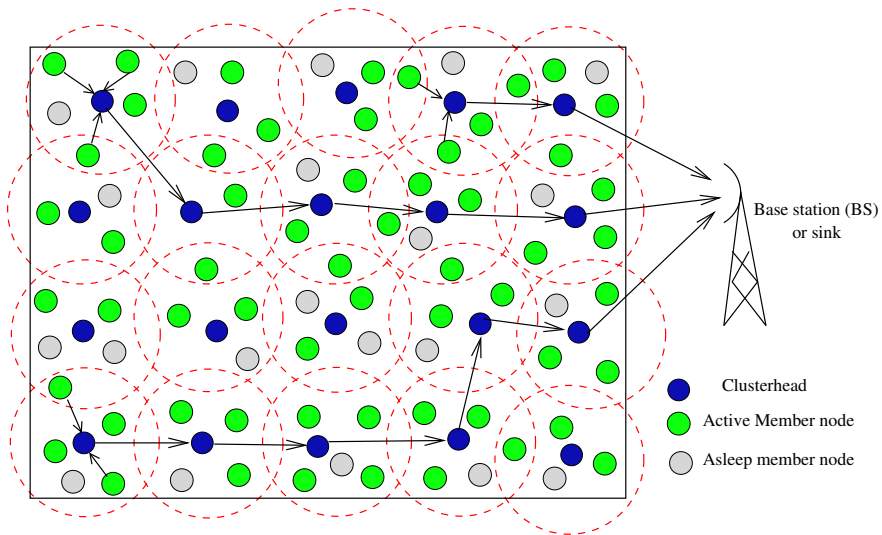


Fig. 1. Cluster-based topology

necessary flooded messages, some routing protocols, mainly geographic ones (Ko & Vaidya, 2000; Lin & Stojmenovic, 2003; Rodoplu & Ming, 1999; Y. Yu & Govindan, 2001) with location awareness, restrict flooding to localized regions. Other protocols that are neither data-centric nor location-based can be qualified as topology-based (Frey et al., 2009). This is the case of routing protocols like those proposed in (He et al., 2003; Sohrabi et al., 2000; Ye et al., 2001).

Flat routing protocols are quite effective in relatively small networks. However, they scale very bad to large and dense networks since, typically, all nodes are alive and generate more processing and bandwidth usage. On the other hand, hierarchical routing protocols have shown to be more scalable and energy-aware in the context of WSN. In hierarchical-based routing, nodes play different roles in the network and typically are organized into clusters. Clustering (Figure 1) is the method by which sensor nodes in a network organize themselves into groups according to specific requirements or metrics. Each group or cluster has a leader referred to as *clusterhead* (CH) and other ordinary member nodes (MNs). The clusterheads can be organized into further hierarchical levels.

As opposed to a flat organization, clustering allows a hierarchical architecture with more scalability, less consumed energy and thus longer lifetime for the whole network. This is due mainly to the fact that most of the sensing, data processing and communication activities can be performed within clusters. Numerous are WSN applications that require simply an aggregate value to be reported to the sink. In such applications, data aggregation at the clusterheads helps to alleviate congestion and save energy. Clustering allows intra-cluster and inter-cluster routing which reduces the number of nodes taking part in a long distance communication, thus allowing significant energy saving in addition to smaller dissemination latency.

In this chapter we consider cluster-based routing protocols to achieve energy efficiency in WSN. Section 2 focuses on clustering from the perspective of data routing and a new classification of cluster-based routing protocols into two classes is proposed. Some representatives of

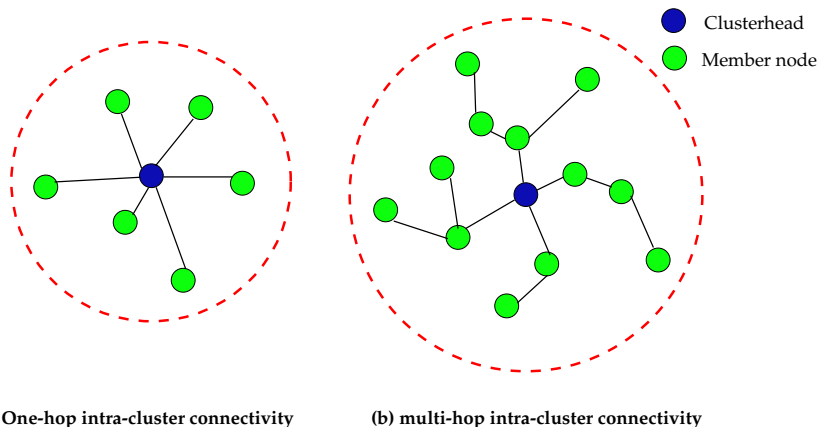


Fig. 2. One-hop toward the sink

both classes are summarized in respectively Sections 3 and 4. Section 5 concludes the chapter with some future research directions.

2. Clustering and Routing in WSN

From a routing perspective, clustering allows to split data transmission into *intra-cluster* (within a cluster) and *inter-cluster* (between clusterheads and every clusterhead and the sink) communication. This separation leads to significant energy saving since the radio unit is the major energy consumer in a sensor node. In fact, member nodes are only allowed to communicate with their respective clusterhead, which is responsible for relaying the data to the sink with possible aggregation and fusion operations. Moreover, this separation allows to reduce routing tables at both member nodes and clusterheads in addition to possible spatial reuse of communication bandwidth.

Intra-cluster communications

Most of the earlier work on clustering assume direct (one-hop) communication between member nodes and their respective clusterheads (*Energy-efficient communication protocol for wireless sensor networks*, 2000; Younis & Fahmy, 2004). All the member nodes are at most two hops away from each other (Figure 2(a)). One-hop clusters makes selection and propagation of clusterheads easy, however, multi-hop intra-cluster connectivity is sometimes required, in particular for limited radio ranges and large networks with limited clusterhead count. Multi-hop routing within a cluster (Figure 2(b)) has already been proposed in wireless ad-hoc networks (Lin & Gerla, 1995). More recent WSN clustering algorithms allow multi-hop intra-cluster routing (Bandyopadhyay & Coyle, 2003; Ding et al., 2005).

Inter-cluster Routing

Earlier cluster-based routing protocols such as LEACH (*Energy-efficient communication protocol for wireless sensor networks*, 2000) assume that the clusterheads have long communication ranges allowing direct connection between every clusterhead and the sink (Figure 3). Although simple, this approach is not only inefficient in terms of energy consumption, it is

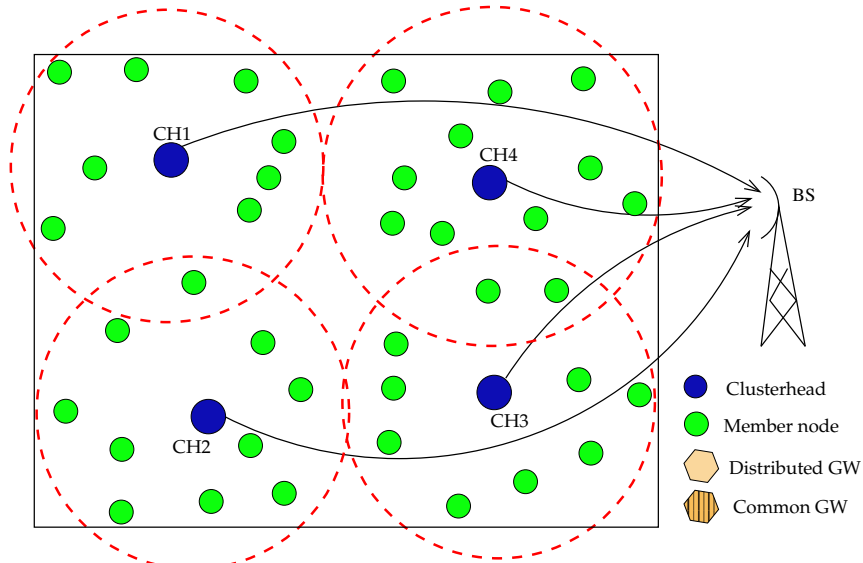


Fig. 3. One-hop toward the sink

based on unrealistic assumption. The sink is usually located far away from the sensing area and is often not directly reachable to all nodes due to signal propagation problems. A more realistic approach is multihop inter-cluster routing that had shown to be more energy efficient (Mhatre & Rosenberg, 2004a). Sensed data are relayed from one clusterhead to another until reaching the sink (Figure 1).

Direct communication between clusterheads is not always possible especially for large clusters (multihop clusters for instance). In this case, ordinary nodes located between two clusterheads could act as *gateways* (GW) allowing the clusterheads to reach each other (Figure 4). A gateway node is either *common* or *distributed*. A common (ordinary) gateway is located within the transmission range of two clusterheads and thus, allows 2-hop communication between these clusterheads. When two clusterheads do not have a common gateway, they can reach each other in at least 3 hops via two distributed gateways located in their respective clusters. A distributed gateway is only reachable by one clusterhead and by another distributed gateway of the second clusterhead cluster.

Inter-cluster communication in several proposals is achieved through organizing the clusterheads in a hierarchy (Figure 5) as done in (Bandyopadhyay & Coyle, 2003) and (Manjeshwar & Agarwal, 2001). Multiple level hierarchy allows better energy distribution and overall energy consumption. However, maintaining the hierarchy could be costly in large and dynamic networks where nodes die as soon as their energy supply is completely discharged.

2.1 Energy Efficiency and Load-balancing

One of the most important objectives of hierarchical organization in sensor networks is energy efficiency that allows longer network lifetime. A clusterhead can perform aggregation and fusion operations on data it receives before relaying it to the base station. In very dense networks, a subset of nodes may be put into the low-power sleep mode provided that these

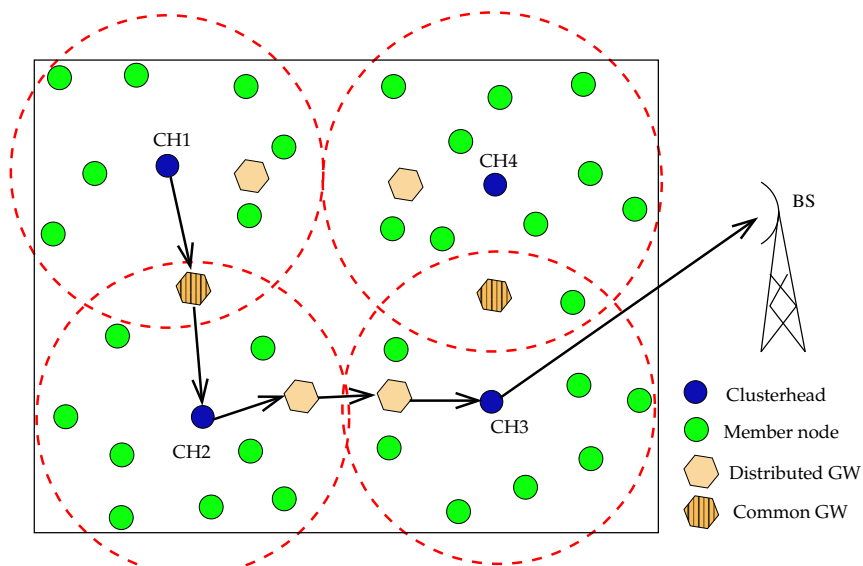


Fig. 4. Multi-hop inter-cluster communication

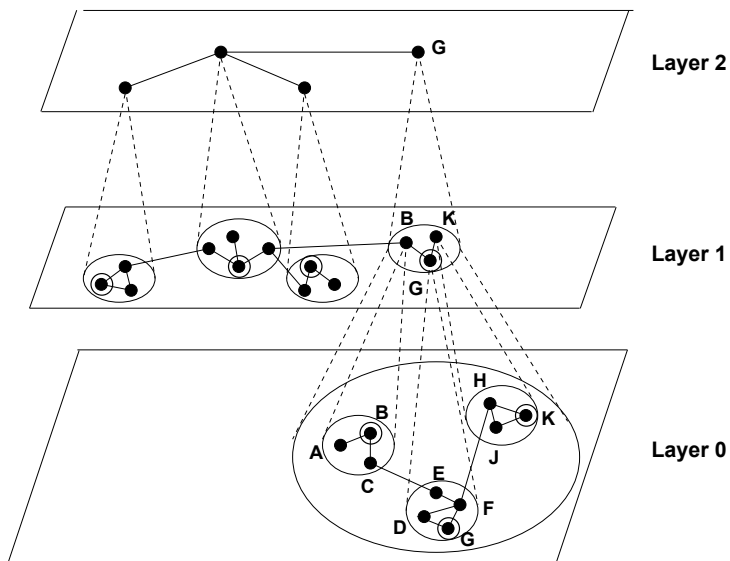


Fig. 5. 3-level hierarchy (redrawn from (Banerjee & Khuller, 2001))

nodes are chosen without affecting the network coverage and connectivity. In this context, a clusterhead can efficiently schedule its member nodes states. Furthermore, medium access collision can be prevented within a cluster if a round-robin strategy is applied among the member nodes. Collisions may require that nodes retransmit their data thus wasting more energy.

Minimizing energy consumption on a per sensor basis is not sufficient to get longer network lifetime, load-balancing is required.

2.1.1 Load-balancing among all nodes

Intra-cluster communications where a member node sends data to its clusterhead for further relaying toward the sink, put a heavy burden on the clusterheads. These latter have, additionally, the responsibility of in-network data operations such as aggregation and fusion. Even if clusterheads are equipped with more powerful and durable batteries, this heavy burden could result in fast battery depletion at the clusterheads and thus shorter lifetime compared to other sensor nodes. This is one possible load unfairness situation that may occur in cluster-based routing. This issue is usually addressed through clusterhead rotation among nodes in each cluster.

2.1.2 Load-balancing among clusterheads

In order to give each clusterhead equivalent burden in the network, many algorithms focus on balancing the intra-cluster traffic load through the formation of nearly equal size (uniform) clusters. In fact, in clusters of comparable coverage and node density, the intra-cluster traffic volume is more likely to be the same for all clusters.

Regarding inter-cluster communication, balanced intra-cluster traffic results in a highly skewed load distribution on clusterheads. In single-hop communication where clusterheads use direct link to reach the base station, the farther the clusterhead, the more energy it consumes and the earlier will die. Even if multi-hop inter-cluster communication is adopted, the nodes close to the base station are burdened with heavier traffic load leading to the so-called *hot spot problem*. This is due to the many-to-one traffic paradigm that characterizes WSN. Nodes in the hot spot area deplete faster their energy and die much faster than faraway clusterheads. This may lead to serious connectivity (network partition) and coverage problems at the base station vicinity.

As a consequence, both intra-cluster and inter-cluster traffic have to be considered jointly when designing a cluster-based routing algorithm. In other words, one has to consider minimizing energy consumption around the sink instead of minimizing the overall consumed energy in the network in order to achieve longer network lifetime. We will report on some work that dealt with this issue in Section 3.5.

2.2 Clustering Algorithms Taxonomy

In the literature, there have been several different ways to classify Clustering algorithms for WSNs. In (Younis et al., 2006), the classification is performed based on parameter(s) used for electing clusterheads and the execution nature of a clustering algorithm which can be either probabilistic or iterative. In iterative clustering techniques, a node waits for a specific event to occur or certain nodes to decide their role (e.g., become clusterheads) before making a decision. Probabilistic Clustering Techniques enables every node to independently decide on its role in the clustered network while keeping the message overhead low. Considering how the cluster formation is carried out, a clustering algorithm is either executed at a central point or

in a distributed fashion at local nodes. Centralized approaches are used by few earlier proposals like LEACH-C (Chandrakasan et al., 2002). They require global knowledge of the network topology and are inefficient in large-scale topologies. A distributed approach, however, is more scalable since a node is able to take the initiative to become a clusterhead or to join an already formed cluster without global topology knowledge.

Authors of (Abbasi & Younis, 2007) classify clustering algorithms according to their convergence rate into two classes : variable and constant convergence time algorithms. The former algorithms have a convergence time that depends on the number of nodes in the network and thus are more suitable to relatively small networks. Constant convergence time algorithms converge in a fixed number of iterations, regardless of the size of the nodes population.

Clustering algorithms can also be classified into homogeneous or heterogeneous (Mhatre & Rosenberg, 2004b) depending on the nature of the deployed sensor network. In heterogeneous environments, the clusterhead roles can be preassigned to nodes with more energy, computation and communication resources. In a homogeneous environment, the clusterheads can be designated in a random way or based on one or more criteria. It is worth mentioning, that even in a homogeneous network, heterogeneity can occur simply in terms of available energy at nodes. As time goes on, some nodes depending on their role and environmental factors, will discharge more quickly their batteries. This is why energy and clusterhead rotation have to be considered in the process of clustering.

Since we report, in this chapter, on clustering techniques and their use to achieve energy efficient routing in WSN, we adopt a different classification. Most proposed cluster-based routing protocols rely on already formed clusters. Afterwards, the inter-cluster communication is generally ensured using traditional flooding among only clusterheads or by recursively executing the clustering algorithm to obtain a hierarchy of clusterheads rooted at the sink. We qualify these protocols as *pre-established* cluster-based routing algorithms. Protocols that build clusters based on packets flowing in the network without a priori construction are qualified as *on-demand* cluster-based algorithms. It is worth mentioning that the second class had always been omitted in surveys like (Younis et al., 2006) (Abbasi & Younis, 2007) and (Mamalis et al., 2009). On-demand clustering by exploiting existing traffic to piggyback cluster-related information, eliminates major control overhead of traditional clustering protocols. Besides, there is no startup latency even if there is a transient period before getting maximum performances.

3. Pre-established Cluster-based Routing Algorithms

In this section, we review most important clustering algorithms. Even if they are limited only to the clusters formation and do not address explicitly inter-cluster routing. It is generally straightforward to apply on top of the clustered topology a routing protocol taking into account only the clusterheads in the route discovery phase.

3.1 Low Energy Adaptive Clustering Hierarchy (LEACH)

Low-Energy Adaptive Clustering Hierarchy (LEACH) (*Energy-efficient communication protocol for wireless sensor networks*, 2000) is one of the most popular hierarchical routing algorithms for sensor networks. LEACH is a cluster-based protocol with distributed cluster formation with random clusterhead election. A sensor node chooses a random number between 0 and 1. If this random number is less than a threshold value, $T(n)$, the node becomes a clusterhead for the current round. This threshold value is calculated using :

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

where P is the desired fraction of nodes to be clusterheads, r is the current round and G is the set of nodes that have not been clusterheads in the last $\frac{1}{P}$ round. The elected clusterheads broadcast an advertisement message to inform other nodes about their states. Based on the received signal strength of the advertisement, a non-clusterhead node decides to which cluster it will belong for this round and sends a membership message to its clusterhead. Based on the number of nodes in the cluster, a clusterhead creates a TDMA schedule and assigns each node a time slot in which it can transmit. This schedule is broadcast to all the cluster nodes. This is the end of the so-called *advertisement* or *setup phase* of LEACH. Then begins the *steady state* where different nodes can transmit their sensed data.

In order to save energy, in the steady phase, the radio of each member node can be turned off until the node's allocated transmission time. Moreover, clusterheads can perform data processing such as fusion and aggregation before relaying to the base station. To evenly distribute energy load among nodes, clusterheads rotation is insured at each round by entering a new advertisement phase and by using equation (1).

LEACH is completely distributed and requires no global knowledge of network. However, it forms one-hop intra and inter cluster topology, which is not applicable to large region networks. Clusterheads are assumed to have a long communication range so they can reach the sink directly. This is not always a realistic assumption since the clusterheads are regular sensors and the sink is often located far away. Furthermore, dynamic clustering brings extra overhead due to the advertisements phase at the beginning of each round, which may diminish the gain in energy. Since the decision to elect a clusterhead is probabilistic without energy considerations, LEACH clusterhead rotation assume a homogeneous network and can not ensure real load-balancing in case of nodes initially with different amount of energy. A node with very low energy becomes a clusterhead for the same number of rounds as other nodes with higher energy and will die prematurely. This could affect network coverage and connectivity.

LEACH-C

LEACH-C (Chandrakasan et al., 2002) is a centralized version of LEACH where only the advertisement phase differs. At this phase, each node sends information about its current location and residual energy level to the sink. Based on nodes location, the sink builds clusters using the simulated annealing algorithm (Murata, 1994) so the amount of energy required by member nodes to transmit their data to their respective clusterhead is minimized. Collected information about nodes energies allows the sink to discard those with energy below the average network energy. Consequently, energy load is evenly distributed among all the nodes.

3.2 Energy Efficient Hierarchical Clustering (EEHC)

Energy Efficient Hierarchical Clustering (EEHC) (Bandyopadhyay & Coyle, 2004) can be seen as an extension of LEACH with multi-hop intra clusters and a hierarchy of clusterheads to route data to the sink. In the single-level clustering of EEHC, each sensor in the network becomes a *Volunteer* clusterhead with probability p . It announces this to the sensors within k hops radio range. Any sensor that receives such advertisements and is not itself a clusterhead joins the closest cluster. If a sensor does not receive a clusterhead advertisement within a certain time duration it can infer that it is not within k hops of any volunteer clusterhead and

hence becomes a *forced* clusterhead. Data transmission to the sink can be performed using multi-hop routing through clusterheads organization in a multi-level hierarchy rooted at the sink. To do so, the single-level clustering is repeated recursively at the level of clusterheads. This distributed process allows EEHC to have a time complexity of $O(k_1 + k_2 + \dots + k_h)$ where h is the number of levels and k_i is the maximum number of hops between a member node and its clusterhead in the i th level of hierarchy. Since spent energy in the network depends on p and k , the authors provide methods to compute the optimal values of these parameters that ensure minimum consumed energy. Simulation results showed significant energy saving when using the optimal parameter values.

3.3 Hybrid Energy-Efficient Distributed Clustering (HEED)

Both EEHC and LEACH do not consider energy in selecting clusterheads. HEED (Younis & Fahmy, 2004) brings one more step toward energy-efficient cluster-based routing with explicit consideration of energy. Selected clusterheads in HEED have relatively high average residual energy compared to member nodes. Additionally, HEED aims to get a well-distributed clusterheads set over the sensor field. Indeed, in HEED, the probability that two nodes within the transmission range of each other to be clusterheads is small. It is worth mentioning that the main drawback of LEACH is that the random election of clusterheads does not ensure their even distribution in the sensing field. It is quite possible to get multiple clusterheads concentrated in a small area. In this case, this area sensors are likely to exhaust their energy more quickly which may lead to insufficient coverage and network disconnection. Distributing clusterheads evenly in the sensing area is one important goal to be met in order to ensure load balancing and hence longer network lifetime.

HEED periodically selects clusterheads according to a hybrid of their residual energy and intra-cluster communication cost. Initially, to limit the initial clusterhead announcements, HEED sets an initial percentage C_{prob} of clusterheads among all sensors. The probability that a sensor becomes a clusterhead is $CH_{prob} = C_{prob} E_{residual} / E_{max}$ where $E_{residual}$ is the current energy in the sensor, and E_{max} is its maximum energy. Afterwards, every sensor goes through several iterations until it finds the clusterhead that it can transmit to with the least transmission power. If it hears from no clusterhead, the sensor elects itself to be a clusterhead and sends an announcement message to its neighbors. Each sensor doubles its CH_{prob} value and goes to the next iteration until its CH_{prob} reaches 1. Therefore, there are two types of status that a sensor could announce to its neighbors:

- **Tentative status:** The sensor becomes a tentative clusterhead if its CH_{prob} is less than 1. It can change its status to a regular node at a later iteration if it finds a lower cost clusterhead.
- **Final status:** The sensor permanently becomes a clusterhead if its CH_{prob} has reached 1.

At the final phase, each sensor makes a final decision on its status. It either picks the least cost clusterhead or pronounces itself as clusterhead. Simulation results showed that HEED outperforms LEACH with respect to the network lifetime and energy consumption distribution. However, HEED suffers from a consequent overhead since it needs several iterations to form clusters. In each iteration, a lot of packets are broadcast.

Clustering Method for Energy Efficient Routing (CMEER)

CMEER (Kang et al., 2007) is another attempt to achieve well distributed Cluster heads. In CMEER, a node declares itself as a candidate to be a clusterhead using equation (1) where P is

chosen higher than adopted values in LEACH. Each candidate advertises its intention to be a clusterhead within its radio range. Each node (even candidate to be a clusterhead) decides to join a given clusterhead based on the received signal strength of the advertisement message. In this way, the authors try to avoid redundant creation of clusterheads in a small area. The simulation results showed that CMEER outperforms LEACH in terms of energy consumption and network lifetime.

3.4 Distributed Energy Efficient Hierarchical Clustering (DWEHC)

Distributed Energy Efficient Hierarchical Clustering (DWEHC) (Ding et al., 2005) aims to improve HEED by generating balanced cluster sizes and optimizing the intra-cluster topology thanks to its location awareness. DWEHC creates a multi-level (instead of one-hop in HEED) structure for intra-cluster communication and limits a parent node's number of children. Each sensor s calculates its weight after locating the neighboring nodes in its area using :

$$W_{weight}(s) = \frac{E_{residual}(s)}{E_{initial}(s)} \times \sum_u \frac{R-d}{6R} \quad (2)$$

where $E_{residual}(s)$ and $E_{initial}(s)$ are respectively residual and initial energy at node s , R is the cluster range (a system parameter that corresponds to how far a node inside a cluster can be from the clusterhead) and d is the distance between s and neighboring node u . In a neighborhood, the node with largest weight would be elected as a clusterhead and the remaining nodes become members. At this stage member nodes are considered as 1-level nodes and communicate directly with the clusterhead. If a member node can reach its clusterhead using more than one hop while saving energy, it will become an h-level member where h is the number of hops required to achieve the clusterhead. Required energy to communicate in a cluster can be computed using node's knowledge of the distance to its neighbors. The cluster range R is used to limit the number of levels.

Even if HEED considers energy reserve in clusterhead selection and aims to a well distributed clusterheads, simulation results showed that clusters generated by DWEHC are more well-balanced and that DWEHC achieves significantly lower energy consumption in intra-cluster and inter-cluster communication than HEED. However, location information required by DWEHC are not necessarily and easily available. Many other location-aware clustering techniques have been proposed in the literature :

Geographic Adaptive Fidelity (GAF)

GAF (Xu et al., 2001) is an energy-aware routing algorithm designed primarily for mobile ad hoc networks, but may be applicable to sensor networks as well. GAF is generally cited as a location based routing protocol but may be considered as a hierarchical protocol where the clusters are based on geographic location. The network area is divided into fixed zones (clusters) that form a virtual grid in which nodes collaborate with each other to play different roles. The virtual grid is defined such that for any two adjacent zones A and B, all nodes in A are able to communicate with all nodes in B, and vice versa. By assuming an ideal radio propagation model and choosing appropriate side length of zones according to the radio transmission range, GAF ensures that a connected backbone network can be formed as long as just one node at time need to be active. That node play a role of a CH and each node uses its location to associate itself with a node in the virtual grid. The clusterhead is responsible for monitoring and reporting data to the Base station. The Nodes associated with the same point on the grid are considered equivalent in terms of the cost of packet routing. Such equivalence

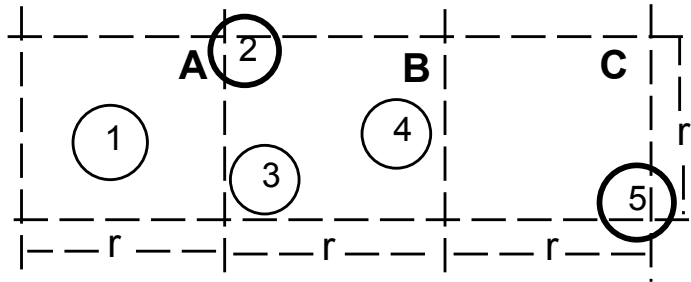


Fig. 6. GAF virtual grids

is exploited in keeping these nodes in sleeping state in order to save energy. Thus, GAF can substantially increase the network lifetime as the number of nodes increases. A sample situation is depicted in Figure 6 redrawn from (Xu et al., 2001). In this figure, node 1 can reach any of 2, 3 and 4 and nodes 2, 3, and 4 can reach 5. Therefore nodes 2, 3 and 4 are equivalent and two of them can sleep.

Nodes change their states from sleeping to active in turn so that the load is balanced in the network. There are three states defined in GAF : (i) *discovery*, for determining the neighbors in the grid,(ii) *active* reflecting participation in routing and (iii) *sleep* when the radio is turned off. The sleeping time is application dependent parameter which is tuned during the routing process. In order to handle the mobility, each node in the grid estimates its leaving time of a grid and sends it to its neighbors. The sleeping neighbors adjust their sleeping time accordingly in order to keep the routing fidelity. Before the leaving time of the active node expires, sleeping nodes wake up and one of them becomes active (a clusterhead). Simulation results showed that GAF performs at least as well as a normal ad hoc routing protocol in terms of latency and packet loss and increases the lifetime of the network by saving energy.

Position-based Aggregator Node Election (PANEL)

PANEL (Buttyan & Schaffer, 2007) is a position-based clustering routing algorithm for WSN. It elects one aggregator node for reliable and persistent data storage applications. PANEL assumes that the sensor nodes are deployed in a bounded area partitioned into geographical clusters. The clustering is determined before the deployment of the network, and each sensor node is pre-loaded with the geographical information of the cluster to which it belongs. At the beginning of each epoch, a reference point is computed in each cluster by the nodes in a completely distributed manner depending on the epoch number. Once the reference point is computed, the nodes in the cluster elect the node that is the closest to the reference point as the aggregator (clusterhead) for the given epoch.

The reference points of the clusters are re-computed and the aggregator election procedure is re-executed in each epoch. This ensures load balancing in the sense that each node of the cluster can become aggregator with nearly equal probability. The communication overhead used in the election procedure is also used to establish the routing tables within the cluster. At the end of the aggregator node election procedure, the nodes also learn the next hop towards the aggregator elected for the current epoch.

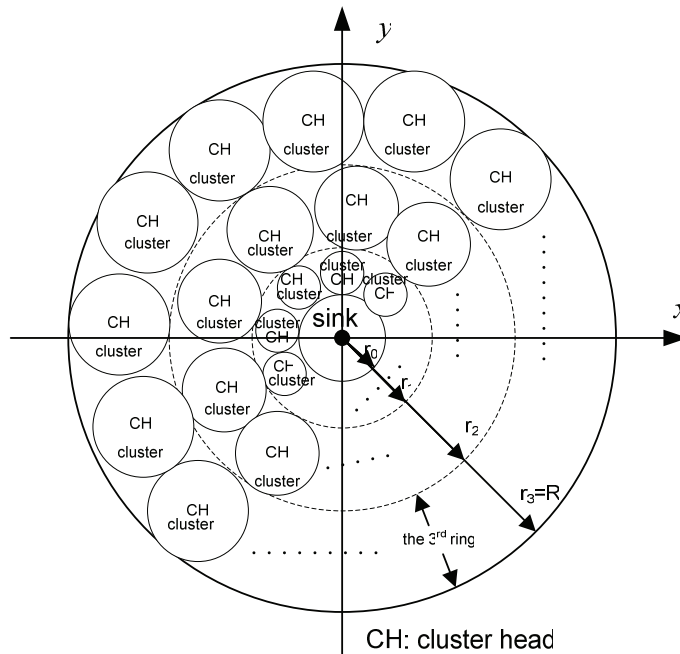


Fig. 7. Unequal size clusters (redrawn from (Shu et al., 2005))

PANEL can be integrated with any position-based routing protocol for inter-cluster communications. The authors proposed to experiment PANEL with the Greedy Perimeter Stateless Routing (GPSR) protocol (Karp & Kung, 2000). Simulation results showed that PANEL outperforms LEACH by about 67% to 83% in terms of network lifetime. This performance gain can be explained by the reduction of the number of transmissions and receptions thanks to data aggregation. However, the main limitation of PANEL is its assumption that the clusters are determined before deployment and thus can not adapt to WSN dynamics.

3.5 Unequal clustering

All the previously cited clustering algorithms form clusters with fixed or variable radius without any consideration of the hot spot problem introduced in Section 2.1.2. One possible solution of this issue is to form unequal clusters depending on how far is a clusterhead from the sink. The rationale behind this is that main spent energy by a clusterhead is due to both inter-cluster and intra-cluster communication and hence have to be considered jointly. On the one hand, intra-cluster communication cost is proportional to the number of member nodes in a cluster. On the other hand, in a multihop network, inter-cluster communication cost depends on the experienced forwarding load by a given clusterhead. In the many-to-one communication pattern of WSN, the closer to the sink, the greater forwarding load a clusterhead have to handle. As a consequence, more uniform load distribution among clusterheads in a network can be achieved through smaller clusters near the base station. Figure 7 redrawn from (Shu et al., 2005) illustrates the main idea behind unequal clustering.

(Soro & Heinzelman, 2005) proposed an Unequal Clustering Size (UCS) model for network organization in order to balance energy consumption of clusterheads in multihop sensor networks, thus increasing network lifetime. Clusterheads are deterministically deployed and are assumed to be much more expensive (super nodes) than simple sensor nodes with the ability to move to adjust their locations, managing at the same time the size of their clusters and the expected load from other clusters further away.

In UCS, the sensing field is assumed to be circular and is split into two concentric circles, called layers. Soro et al. showed through both theoretical and experimental analysis, that the size of the cluster in the inner layer should be reduced to get more uniform energy consumption. For both homogeneous and heterogeneous networks, they showed that UCS achieves an improvement of about 10-30% over the Equal Clustering Size (ECS) scheme, depending on the aggregation efficiency of the clusterheads.

(Shu et al., 2005) aimed to design optimal power allocation strategies to achieve power balance among clusterheads that maximize the network lifetime, defined as the time until one clusterhead runs out of battery. The problem of balancing energy consumption among clusterheads is formulated as a signomial optimization problem. Like (Soro & Heinzelman, 2005), Shu et al. split the monitoring area into layers and studied how to achieve load balance by assigning larger cluster sizes to clusterheads that are responsible for less data forwarding as shown by Figure 7. They derived optimal parameters, such as the cluster radius of each layer and the relay probabilities of clusterheads, to prolong the network lifetime. The study demonstrates the significance of simultaneously considering the impacts of intra- and inter-cluster traffic.

Shu et al. stressed the importance of joint design of clustering strategies and routing since the volume of relayed traffic is also affected by the underlying routing scheme. They provided two schemes for balancing power consumption : routing-aware optimal cluster planning and clustering-aware optimal random relay. The former is essentially a clustering approach that is developed in the context of shortest-hop-count inter-clusterhead routing. For this scheme, the optimal cluster size and location are obtained. The latter is essentially a routing strategy for "load-balanced" clustered topologies (i.e., all clusters are of the same size). According to this approach, a clusterhead probabilistically chooses to either relay the traffic to the next-hop clusterhead or to deliver it directly to the sink.

For practical deployment of such schemes, several issues are still open for research, mainly how to optimally select cluster sizes without knowledge of the node locations and without assuming deterministic clusterheads deployment.

3.6 QoS-aware Cluster-based Routing protocols

Numerous routing protocols try to achieve QoS requirements such as end-to-end delay and available bandwidth when building paths in a sensor network. Threshold sensitive Energy Efficient sensor Network protocol (TEEN) (Manjeshwar & Agarwal, 2001) is one of cluster-based routing protocols that aims to responsiveness to sudden changes in time-critical applications. TEEN builds a 2-tier clustering topology as depicted in Figure 8 and relies on broadcasting hard and soft thresholds by each clusterhead to its member nodes. Hard threshold is the absolute value of the attribute beyond which, the node sensing this value must switch on its transmitter and report to its clusterhead. The nodes will next transmit data only when the current value of the sensed data is greater than the hard threshold and differs from the previously sensed value by an amount equal to or greater than the soft threshold. This allows significant decrease of the number of transmissions. Hard and soft threshold values can be adjusted so the data traffic can be controlled.

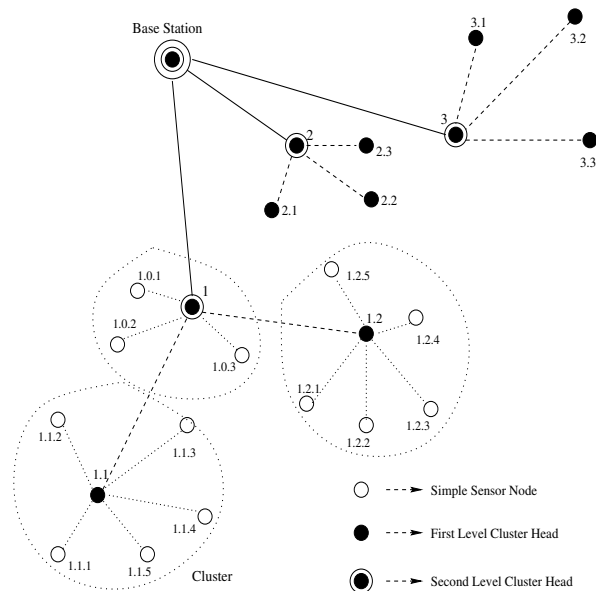


Fig. 8. TEEN hierarchy clustering (redrawn from (Manjeshwar & Agarwal, 2001))

TEEN is quite limited in applications where periodic reports are needed since the user may not get any data at all if the thresholds are not reached. The Adaptive Threshold sensitive Energy Efficient sensor Network protocol (APTEEN) (A. Manjeshwar, 2002) is an extension to TEEN aiming to handle applications with periodic data collections while being sufficiently reactive to time-critical events.

Recent research effort aimed to guarantee WSN specific requirements such as connectivity and coverage in cluster-based routing protocols while being energy efficient. (Soro & Heinzelman, 2009) tackled the problem of clusterhead election with entire area coverage preservation. Based on different coverage-aware cost metrics, nodes more important to the network coverage task are less likely to be selected as clusterheads. The same metrics are used to find the set of active sensor nodes that provide full network coverage, as well as the set of routers that forward the clusterheads' data load to the sink. Soro et al. showed that clustering in sensor networks should be performed with joint consideration of remaining energy and coverage redundancy. Their proposed approach showed to maintain full coverage of the monitored area from 25% to $4.5\times$ with respect to a traditional approach where only residual energy or coverage redundancy are considered separately.

Authors of (Chamam & Pierre, 2009) argue that coverage, connectivity of sensors to clusterheads and routing have to be taken into account within the same global planning process in building a clustering topology. When coverage and connectivity are dealt with separately, the obtained configuration may not be optimal. For example, an optimal covering subset of sensors can fail to guarantee network connectivity because some nodes are switched off or the optimally designated clusterheads may belong to the set of switched-off sensors. Motivated

by this fact, Chamam et al. addressed the global problem of maximizing network lifetime under the joint clustering, routing, and coverage constraint. They formulated the problem as an Integer Linear Programming model, proved that it is NP-Complete and implemented a Tabu search heuristic to tackle the exponentially increasing computation time of the exact resolution.

4. On-demand Cluster-based Routing Algorithms

In this class of cluster-based routing algorithms, the clustering topology is built in parallel with the routing discovery phase.

4.1 Passive Clustering (PC)

Passive clustering (PC) (Kwon & Gerla, 2002) is an *on demand* clustering algorithm. It provides scalability and practicality for choosing the minimal number of forwarding nodes in the presence of dynamic topology changes. PC constructs and maintains the cluster architecture based on outgoing data packets piggybacking *cluster related information*. Passive clustering eliminates setup latency and major control overhead of traditional clustering protocols by introducing two innovative mechanisms for the cluster formation: “*first Declaration wins*” rule and “*gateway selection heuristic*”. With the “*first Declaration wins*” rule, a node that first claims to be a clusterhead *rules* the rest of nodes in its clustered area. The “*gateway selection heuristic*” provides a procedure to elect the minimal number of gateways.

The algorithm defines several states in which a node can be. At cold start, all nodes are in the initial state. Nodes can keep internal states such as *clusterhead-ready* or *gateway-ready* to express their readiness to be respectively a clusterhead or gateway. A candidate node finalizes its role as a clusterhead, a gateway (Full-GW or Dist-GW) or an ordinary node. Additional fields suggested by PC in the message header of each packet are :

- *id* : the identity of the originator of this message,
- *state* : this packer sender status in the network,
- *CH1* and *CH2* : these two fields are only used by a gateway to announce its two clusterhead addresses,

The reactive nature of PC motivated its combination with on demand routing protocols. Originally, PC was applied to reactive routing protocols like AODV (C. Perkins, 1999) and DSR (Johnson et al., 2001). The major overhead in these routing protocols is caused by the flooding of route queries. It was suggested to allow only non-ordinary nodes to rebroadcast query messages.

The PC algorithm presents some shortcomings that have been targeted by several works. In (Rangaswamy & Pung, 2002), the authors proposed to add alive packets to keep the cluster stability as it depends highly on the data packet traffic. Also, a sequence numbering to synchronize packets arriving from a source node is proposed. In fact, if packets containing different states arrive out-of-order at the destination (i.e., the sending node changed its state between transmission of multiple packets) then the destination node will be misled about the true state of the source node. In addition, unnecessary rebroadcasts are eliminated when the final destination of the message is a cluster member.

In WSN, the PC algorithm was proposed in combination with directed diffusion (DD) in (Handziski et al., 2004) to mainly achieve energy efficiency. The main idea of the combination is to save energy in the flooding phases by allowing only clusterheads and gateways to

participate in them. Member nodes are only allowed to send data messages in the data sending phase. Under different network size and load, the combination showed best performances in terms of delivery ratio and average dissipated energy.

Motivated by the results shown in (Handziski et al., 2004) when applying the original PC along with directed diffusion paradigm other works have been proposed in order to achieve better performance of the combination. In (Mamun-or-Rashid et al., 2007), the selection of clusterheads and gateways are done using a heuristic of residual energy and distance. By using residual energy the flooding nodes are chosen in an energy efficient manner. Distances are used to reduce overlapping region and so the number of gateways. The solution proposes to apply a periodic sleep and awake among cluster members. This technique is similar to the one proposed in LEACH and requires a synchronization process between nodes.

4.2 Energy Level-based Passive Clustering (ELPC)

The main idea in combining PC to DD is to reduce energy consumption by minimizing flooding. As this process is known to be very costly, the energy expenditure of the flooding nodes will be much higher than those of ordinary nodes. This will cause a variance in available energy at the nodes in the network and by that a fast partitioning of the network. In PC, topology construction is done according to the lowest ID. The drawback of doing so is its bias towards nodes with smaller IDs leading to their fast battery drainage.

In (Zeghilet et al., 2009), ELPC (Energy Level-based Passive Clustering) is proposed to achieve energy efficiency in terms of network lifetime and not only in terms of energy consumption. This is done through alternating flooding nodes role (clusterheads and gateways) among nodes depending on their energy. The aim of doing so is to have the same amount of energy at all the nodes at a given time which increases substantially the whole network lifetime.

In ELPC, the node's battery is split into levels. One can make a correspondence between different energy levels of a node and virtual sub-batteries it consumed sequentially. The energy level (l) of a node can be computed using :

$$l = \left\lceil L \frac{E_r}{E_i} \right\rceil \quad (3)$$

where E_r is the remaining energy, E_i is the initial one and L is the suggested number of levels. The notion of *candidature* to be a clusterhead or a gateway is introduced by defining the *network energy level (nel)* parameter. A node is not allowed to declare itself as a clusterhead (or a gateway) if its energy level is lower than this parameter. A clusterhead (or a gateway) can keep its role as long as its energy level is higher than the *nel*. Otherwise, it gives up its role and passes to the initial or ordinary state according to whether it knows or not a clusterhead in its vicinity.

The network energy level depends on the energy level of the network nodes and can be viewed as the minimum level of energy necessary for a node to be a clusterhead or a gateway. Zeghilet et al. suggested to take an initial value that corresponds to the half of the battery charge. This value is decreased locally each time the condition to be a clusterhead is not satisfied. The local network energy level is then propagated within outgoing packets header. Each time a node receives a smaller *nel* value, it updates its local value accordingly. ELPC uses the same states as suggested in (Kwon & Gerla, 2002) where a node is initially at the *initial* state. Nodes form and maintain the clustering topology by changing their internal and external states based on outgoing messages. When sending the next message, the node

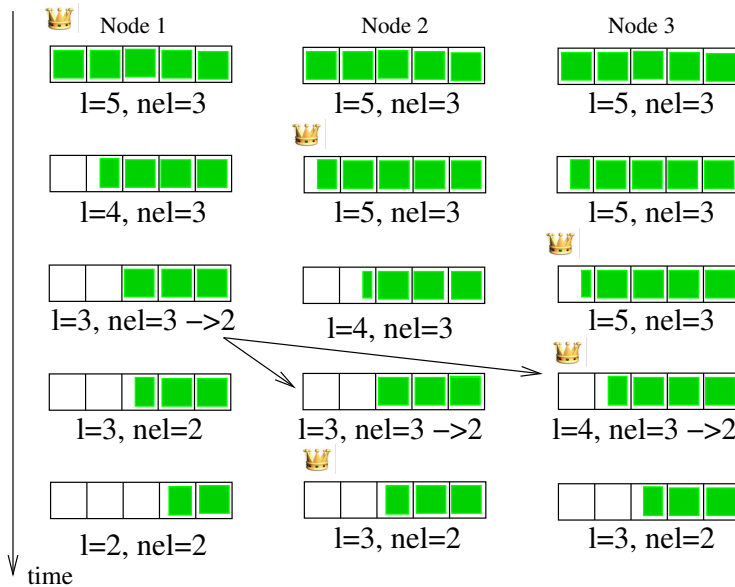


Fig. 9. ELPC and load-balancing feature

announces its external state which becomes visible in the network. ELPC adds the following fields to the packet header :

- *l*, node's energy level
- *nel*, the network energy level
- *give-up*, as in (Handziski et al., 2004) is set when the node is a clusterhead that gives-up its role. It is used to replace the *give-up* message proposed in (Kwon & Gerla, 2002). In ELPC, this field is set when the energy level of a clusterhead drops below the (*nel*).

Figure 9 illustrates how clusterhead rotation is achieved in ELPC. Assume that three nodes 1, 2 and 3 (with same initial amount of energy) are contending to be a flooding node (CH in this example). If we use PC algorithm, node 1 will be selected to be a clusterhead since it has the smallest ID. In ELPC, assume that the number of energy level is 5 and that the *nel* is initially set to 3. We can see that the clusterhead role is alternated between the three nodes depending on their energy levels. When two nodes have the same energy level, then the nodes' identities are used to solve conflict in declaring roles. At step 3, we can note that node 1 decreases its *nel* to 2 and propagates this new value to its neighbors so all nodes can have same estimation of the network energy level.

Figure 10 shows the establishment of routing structures of directed diffusion when this latter is used in combination with ELPC. At initialization, all nodes in the network are in the Initial state. Nodes will use the first interest messages to establish the new topology. A possible topology is illustrated in Figure 10(a-b). After establishing the gradient (Figure 10(c)) and path reinforcement (Figure 10(d)), the source begins sending the sensed data. When the energy level falls under the network energy level at node A (Figure 10(d)), it gives-up its role as clusterhead. Thus, a new topology is established (Figure 10(e)). This is done using next

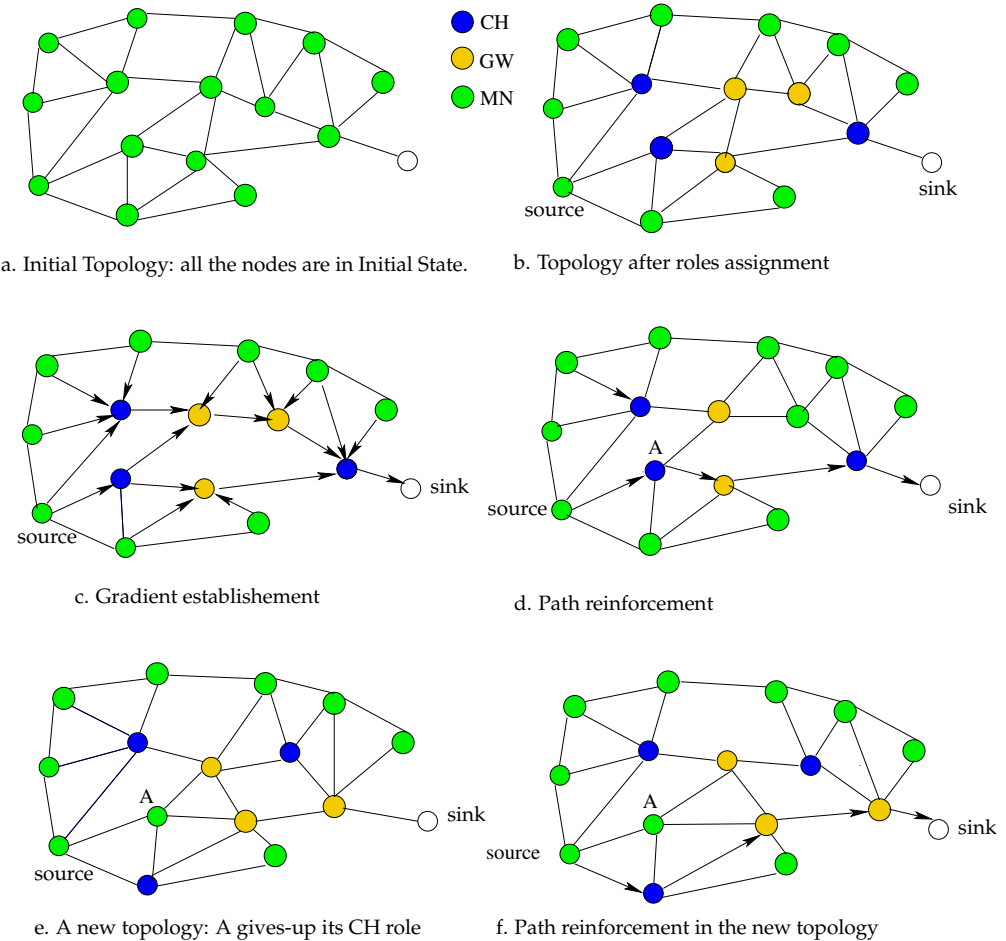


Fig. 10. ELPC illustrated

circulating messages in the network (data messages, interests, explorers data). The resulting PC can be applied to any routing protocol in sensor networks as they mostly rely on flooding and particularly with DD. This not only reduces energy consumption as in (Handziski et al., 2004), but increases the whole network lifetime.

Simulation results showed that ELPC outperforms PC and PCDD (a PC/DD combination without considering energy) in terms of energy consumption and network lifetime thanks to its energy-aware flooding nodes rotation. Figure 11 plots as the network size increases, the network lifetime for the three protocols and shows that ELPC achieves better performances compared to the two others.

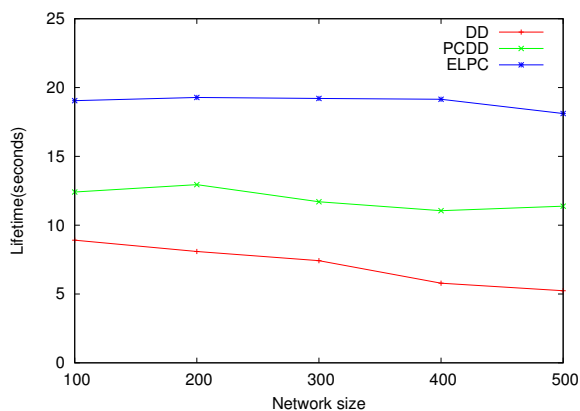


Fig. 11. Network lifetime of ELPC compared to PCDD and DD

4.3 CLIQUE

The work in (Forster & Murphy, 2009) presents CLIQUE, an approach for clusterhead selection based on machine learning (Q-learning). The authors observed that a clusterhead may require less energy than its direct neighbors in a multi-hop intra-cluster topology. They conclude that clusterhead role assignment must take into account not only the current state of the selected clusterheads, but also those of its neighbors and nodes on the paths to the clusterhead. In CLIQUE, clusterhead roles are neither explicitly assigned nor do the nodes need to agree on a clusterhead. Instead, each node decides on a per-packet basis whether to act as clusterhead (aggregating some packets then sending the result to the sinks) or to forward the packet to a better suited neighbor. Authors claimed that this role-free scheme makes the algorithm flexible and robust and eliminates the need for multiple clusterhead selection rounds.

Forster and Murphy focused on the clusterheads selection process and assumed that clusters are predefined (rectangular grids) and that each node knows the identity of the cluster to which it belongs. They targeted a traditional, periodic data reporting application and a multiple sinks network. The sinks flood the network with DATA REQUEST packets announcing their data interest. These packets can carry some routing information that is further used by nodes to estimate the routing cost to the sinks. The routing cost is calculated using a combination of hop counts to reach the sinks and battery status of the nodes on the routes to the sinks. Each sensor node is an independent learning agent, and actions are routing options using different neighbors as the next hop toward the clusterhead. The clusterhead is defined as the cluster node with the best (lowest) routing cost to all sinks.

Even if CLIQUE may incur more energy consumption due to possible coexistence of multiple clusterheads in one cluster, the authors showed through simulations that CLIQUE saves up to 25% of consumed energy thanks to its lower overhead. However, CLIQUE is more suitable for regular data reporting and its performances are to be proved for other types of applications such as event driven ones.

5. Conclusion

Hierarchical (cluster-based) routing protocols hold a great potential toward energy efficiency in WSN. Clustering algorithms have been a hot research area in the last few years. In this

chapter, we introduced a new classification of clustering techniques from the perspective of data routing process. We summarized some protocols that we found to be representative of both classes and that give solution (even partial) of a given problem or requirement of energy efficient clustering.

Managing energy consumption individually at each sensor is far from being sufficient to maximize the WSN lifetime. A global management strategy with load balancing feature is required. To do so, clustering techniques have to provide low overhead clusterhead rotation as well as optimal traffic distribution among clusterheads while keeping network connectivity and coverage. Unequal clustering where both intra-cluster and inter-cluster communications are considered is very promising. However, practical techniques need to be developed to build such clusters without knowledge of the global network topology.

Optimal (or even approximate) parameters estimation for successful clustering is very important but is not an easy task since WSN-specific constraints like energy, coverage and connectivity have to be satisfied. These parameters include mainly clusterheads rotation frequency that allows the best load balance with the lowest overhead, in addition to the number of clusters and their size that maximize the network lifetime.

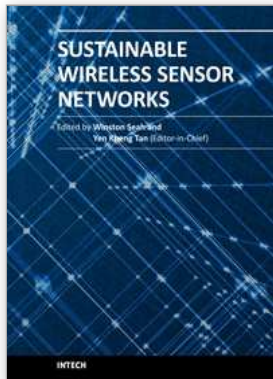
Finally, network dynamics have to be handled appropriately. Network dynamics include possible nodes or sink mobility and topology changes due to death of one or more sensors in the field of interest. Suitable and very reactive solutions have to be provided mainly when a clusterhead dies leaving orphan sensors, possible uncovered area and lack of inter-cluster connectivity.

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Sustainable Wireless Sensor Networks

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Wireless Sensor Networks came into prominence around the start of this millennium motivated by the omnipresent scenario of small-sized sensors with limited power deployed in large numbers over an area to monitor different phenomenon. The sole motivation of a large portion of research efforts has been to maximize the lifetime of the network, where network lifetime is typically measured from the instant of deployment to the point when one of the nodes has expended its limited power source and becomes in-operational – commonly referred as first node failure. Over the years, research has increasingly adopted ideas from wireless communications as well as embedded systems development in order to move this technology closer to realistic deployment scenarios. In such a rich research area as wireless sensor networks, it is difficult if not impossible to provide a comprehensive coverage of all relevant aspects. In this book, we hope to give the reader with a snapshot of some aspects of wireless sensor networks research that provides both a high level overview as well as detailed discussion on specific areas.

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