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COMMUNICATION NETWORKS

Energy consumption balancing (ECB) issues and mechanisms in wireless sensor networks (WSNs): a comprehensive overview

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ABSTRACT

Wireless sensor networks comprise of a large number of low cost sensor nodes that have strictly restricted sensing, computation and communication capabilities. In addition to this, sensor nodes have limited battery life which is not rechargeable in many applications. Due to resource limitations for the sensor nodes, it is important to use energy efficiently for each sensor node. This will result in prolonged network lifetime and functionality. Energy consumption balancing (ECB) property ensures that the average energy dissipation per sensor is equal for all sensors in the network. ECB can be considered as energy efficiency property that optimally manages energy consumption of sensors to prolong network lifetime. This paper investigates the ECB theory and ECB related mechanisms. A classification of ECB mechanism is given by surveying the current and state of the art research in this area. In addition, comparison and main constraints of the mechanisms are presented. Copyright © 2011 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Recent developments in micro-electro-mechanical systems (MEMS) technology, wireless communications and digital electronics have led to the introduction of sensor nodes which are small, low cost and capable of sensing, communicating and computing [1]. Collaboration of these sensor nodes comprises Wireless Sensor Networks (WSNs). Because of its significant capacity, WSN opens up frontiers for many new applications. WSN is a wireless network consisting of spatially distributed sensor nodes. These nodes monitor the physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations [2]. WSNs have gained worldwide attention academically as well as industrially because of its great potential for many applications in various scenarios such as military target tracking and surveillance, natural disaster relief, biomedical health monitoring, hazardous environment exploration, and seismic sensing [3].

Unlike traditional networks, WSNs have distinctive features and limited resources. Dynamic topology, vast number of nodes, application and environment dependency are the distinctive features of WSNs. Resource constraints include short communication range, low bandwidth, limited processing, and limited energy resource. Energy resource is battery of sensor node which is not rechargeable in many applications [1]. Furthermore, due to the large scale of the network, it is not practical, or even not possible, to replace or recharge the batteries of the sensors. Hence, duration of battery is considered lifetime of a sensor. In this respect, energy efficiency is crucial and essential in WSN to prolong network lifetime.

Earlier researchers focused on minimising energy consumption of individual sensor nodes to attain energy efficiency whereas later researchers realised that minimising overall energy resource of WSNs is more important to prolong network lifetime. Minimising energy consumption of overall network is called energy consumption balancing. Energy consumption balancing (ECB) property ensures that the average energy dissipation per sensor is equal for all sensors in the network [4]. ECB can be considered as energy efficiency property that optimally manages energy consumption of sensors to prolong network lifetime. So, main goal for ECB is uniform energy dissipation which ensures that a network remains fully functional for the maximum

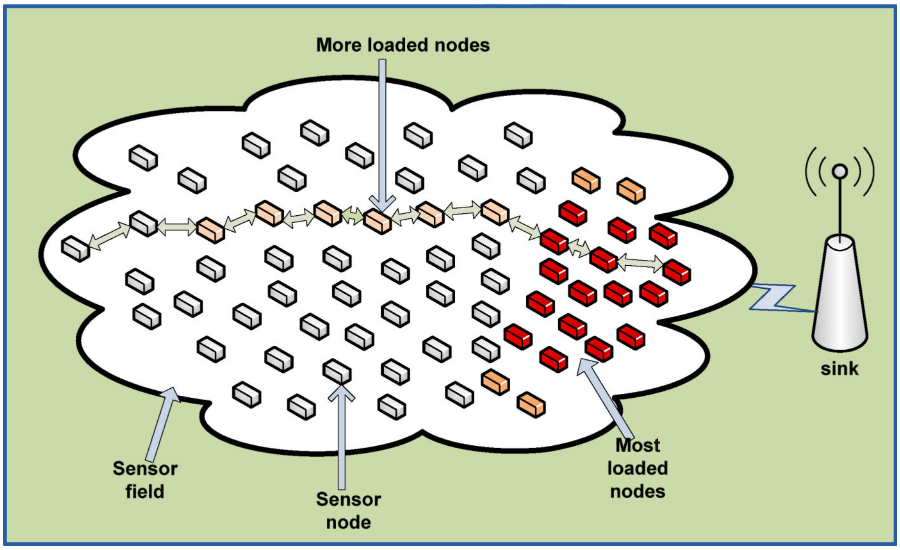

Figure 1. Example of unbalanced energy consumption among nodes using multihop mode communication in WSN.

time. Since main objective of WSN is to obtain data about sensor field using sensor nodes that collaborate together, equal energy consumption of each sensor is essential for a fully functional network.

On the other hand, imbalanced energy consumption induces network disconnections, energy holes and data incompleteness. Figure 1 shows an example of energy imbalance in typical network scenario. The base station (BS) is located on the right side of WSN and sensors send data to BS in multihop mode in Figure 1. The sensors nearer to BS are overburdened because of relaying of other sensors' data to BS. As a consequence, nearer sensors consume much more energy and die much faster which results in the network disconnections and data incompleteness about sensor field.

ECB mechanisms deal with distributing the communication and computational load among nodes by different techniques so that energy consumption of sensors is uniform. On the other hand, ECB might not be always feasible or desirable. Since ECB property requires some network features or method, all applications might not support to implement it. Moreover, some applications do not loose its functionality although some percentages of nodes finish their energies. Hence, depending on the application, ECB property can be classified as applicable, necessary, or inapplicable. ECB issues and mechanisms can be different depending on the network parameters such as node deployment and capability as well as sink node options. For instance, in the example shown in Figure 1, ECB issue is severe and deploying more sink nodes can mitigate the problem by distributing load more equally over the network.

Considerable research has been focused at overcoming ECB issues, prolonging network lifetime through different ECB mechanisms based on network configuration and application type. This survey paper provides a comprehensive overview of these ECB mechanisms proposed in the literature for WSNs. We survey state of the WSN research and summarise a collection of published mechanisms asserting their features and constraints. Further, we also compare the different mechanisms and analyse their applicability. In the next section, we present overview of ECB. In Section 3, we summarise a collection of ECB mechanisms for WSNs and present classification of the various approaches pursued. Finally, Section 4 concludes the paper.

2. OVERVIEW OF ECB

Energy models in WSN mostly consider energy consumption for two tasks: processing and communication [5–7]. Amount of energy consumption of a node may differ depending on hardware (sensor node) and task in the network [8] but this is not the source of energy imbalance issues. Generally, unequal distribution of communication and data processing among sensors results in ECB issues [9, 10–14]. This event is quite common in WSN where multihop communication is adopted. Multihop communication fulfils constraints of a sensor node such as efficient energy usage and short-range communication. On the other hand, it causes energy imbalance because of unequal communication load. Further, in clustered WSN, cluster heads perform additional data processing tasks which require more energy consumption than other nodes. Overburden in communication tasks of sensors is more severe and it mainly contributes to ECB issues [12, 13].

To illustrate this phenomenon we analyse energy consumption in a simple linear network using prominent energy (radio) model [5]. According to this model energy consumption for transmitting k bit of data is calculated as follows [5]:

$$E_{T_x}(k, d) = E_{\text{elec}} \times k + \varepsilon_{\text{amp}} \times k \times d^2 \quad (1)$$

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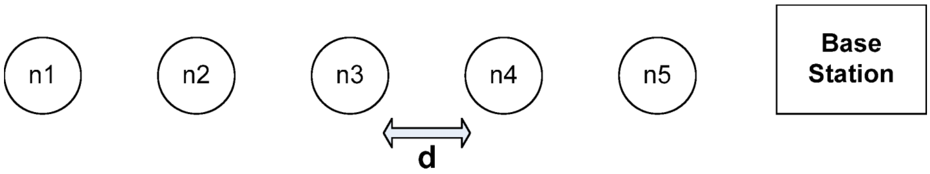

Figure 2. Simple linear network.

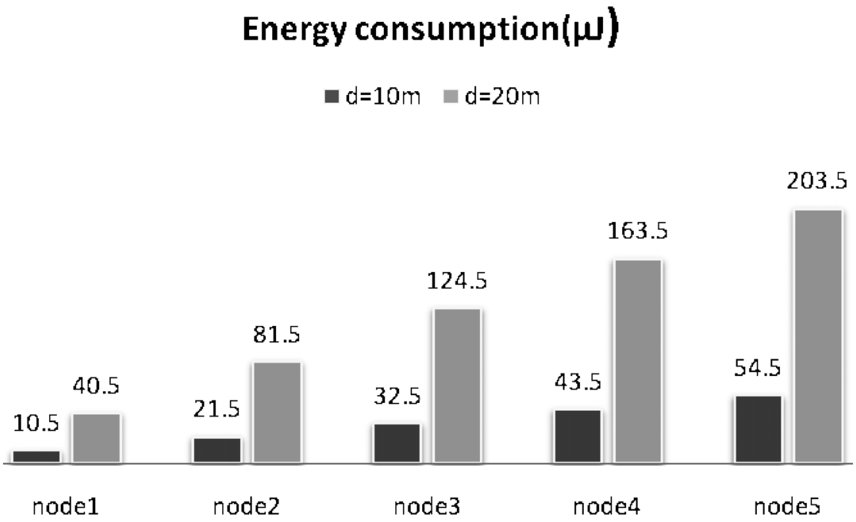

Figure 3. Energy consumption distribution.

Table I. Energy consumption distribution.

Node energy consumption (μJ)	node1	node2	node3	node4	node5
$d = 10$ m	10.5	21.5	32.5	43.5	54.5
$d = 20$ m	40.5	81.5	124.5	163.5	203.5

where E_{elec} is transmitter electronics which is considered to be 50 nJ/bit, ε_{amp} is transmit amplifier which consumes 100 pJ/bit/m^2 and d is communication distance. To receive data, energy consumption is different [5]:

$$E_{R_x}(k) = E_{elec} \times k \tag{2}$$

We consider a simple linear network which consists of five sensor nodes and one BS as shown in Figure 2.

In this network, sensor nodes send their data to BS in a multihop mode and distance between nodes is equal. Node 1 is the furthest node from BS and the closest node to BS is node 5. Each node sends 10 bits of data to BS. As we can see from the results in Figure 3, node 5 consumes more energy than node 1 since it is the most loaded node in this example. Hence, node 5's energy will be drained five times faster than node 1. The problem is more severe when distance between nodes is larger as it is shown in Figure 3. Corresponding values are shown in Table I.

ECB is associated with node distribution, transmission power control, application type and base station option as shown in Figure 4.

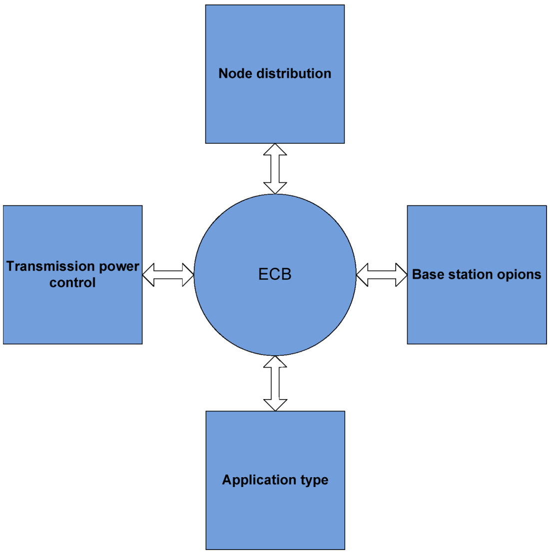

Figure 4. ECB associated factors.

2.1. Node distribution

Sensor node distribution strategy has strong influence on ECB. Since it is related with distribution of load, it shows the general picture of load distribution in the network. Hence, depending on the node distribution scheme, ECB issues and mechanisms can be different. For instance, in

Reference [15] authors proposed two node deployment schemes to attain ECB in network. The main principle is to deploy nodes in descending distance or ascending density towards BS.

On other hand, it is not viable in all applications to distribute or deploy nodes as aimed; instead some application requires random dropping of nodes or non-uniform node deployment which might make ECB issue more complicated.

2.2. Base station options

Base station (sink) location regulates the direction of data traffic in multi-hop WSN (see Figure 1). From this point of view, communication load is in ascending order towards BS which causes energy imbalance. On the other hand, when sink is mobile, ECB issues and mechanisms will be different. Mobile sinks change their location when the nearby sensors' energy becomes low. In choosing a new location, a sink searches for zones with richer sensor energy so that ECB is maintained over the network. Moreover, multiple sinks node deployment might mitigate the ECB issues. Setting up multiple sinks helps to distribute the communication load over the network.

2.3. Application type

Applications of WSN are various which imply different network parameters. Applications can be categorised into two fields: periodic and event-responded monitoring. Depending on the cases, ECB issues can be more severe for periodic monitoring applications than event-responded monitoring. Since, in periodic monitoring, data is sent periodically by the same sensors and after a certain time interval. However, in event responded monitoring, whenever event is detected, data is sent. In the latter case, sensor nodes can select their neighbours who have more energy to send data to BS so that ECB is attained among sensor nodes. Furthermore, depending on the application, ECB can be either necessary or optional. For instance, some applications do not lose its functionality even when some percentage of nodes dies. On the other hand, some applications require full data about sensor field and even dying of a single node influence the network functionality significantly. So, in this case ECB is necessary property for network. Hence, depending on the application, ECB property might be either applicable or not.

2.4. Transmission power control

Transmission power control is another related factor for ECB. Simply fixed transmission power might result in extreme energy imbalance and energy inefficiency. Utilising some intelligent transmission power control to distribute traffic optimally might be helpful to attain ECB [16].

ECB issues are severe since they are related directly with network lifetime and functionality. Reduced network lifetime can be considered utmost important ECB issue. Network lifetime is the time span from the deployment to the instant when the network becomes non-functional [14]. When a network should be considered non-functional is, however, application-specific. It can be, for example, the time when the first sensor dies, a percentage of sensors die, or the network is partitioned. So, either case, dying of first node or some percentage of nodes causes reduced network lifetime and functionality. Furthermore, data incompleteness about sensor field arises whenever some nodes die prematurely in the network. This might be serious problem for some applications. Also, it degrades the network functionality as main function of WSN is to obtain data about sensor field. Another ECB issue is energy hole. Whenever some nodes die prematurely in the network, depending on the location of died nodes, energy holes might be formed. If the dead nodes were located in critical locations then tendency of forming energy holes would be higher which causes network disconnections.

3. ECB MECHANISMS

Considerable research have been done on energy consumption balancing (ECB) among nodes to guarantee network functionality and increase in the network lifetime. We classify ECB mechanisms into three groups as shown in Figure 5:

- node deployment;
- load balancing;
- energy mapping and assigning.

3.1. Node deployment mechanism

Node deployment mechanisms attain ECB by deploying denser nodes where load is more and proposing different sink node options to distribute the load of communication equally [17]. Node deployment mechanisms can be classified into two groups: sensor node deployment and sink node options. Their further classification is shown in Figure 6.

3.1.1. Sensor node deployment.

There are three types of ECB mechanisms that are attained using sensor node deployment: distance-based, density-based and relay node deployment [12, 15, 18–20] as shown in Figure 4. The basic idea in the former two schemes is to control the node placement based on either distance or density. The principle in the latter mechanism is either to deploy some heterogeneous nodes in network where load is more or assign different initial energy to nodes.

3.1.1.1. Distance-based In Reference [15] two node deployment techniques, namely distance-based and

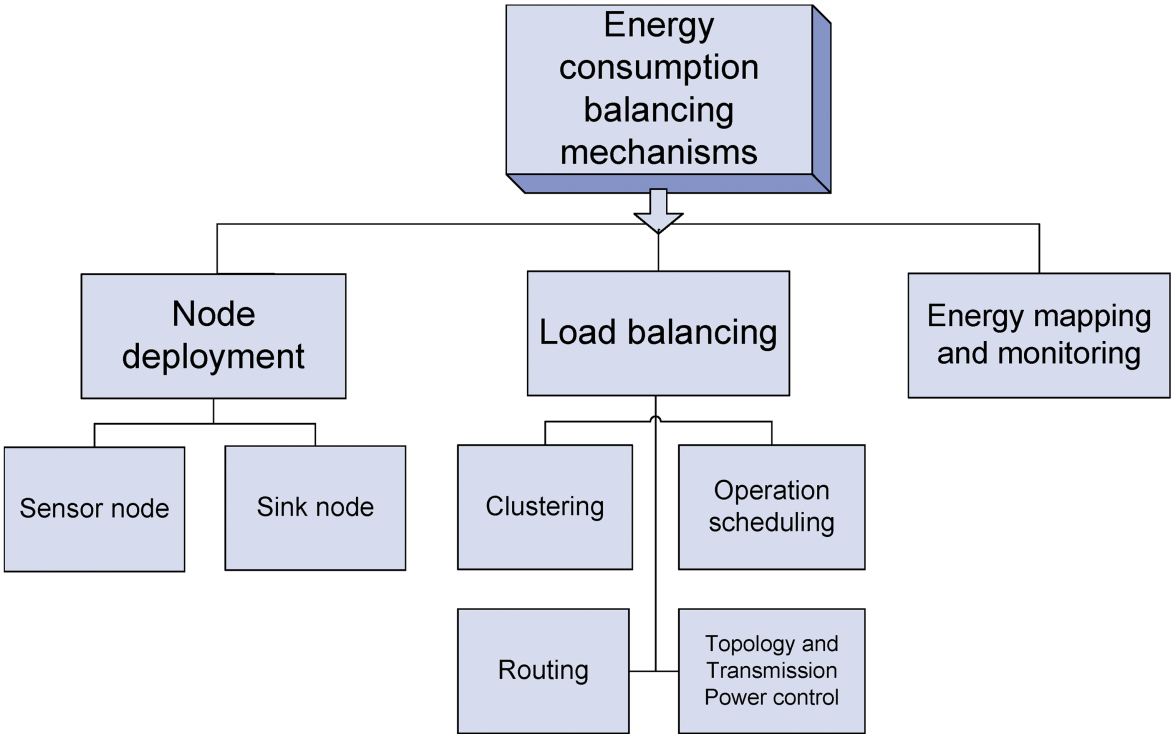

Figure 5. Classification of ECB mechanisms.

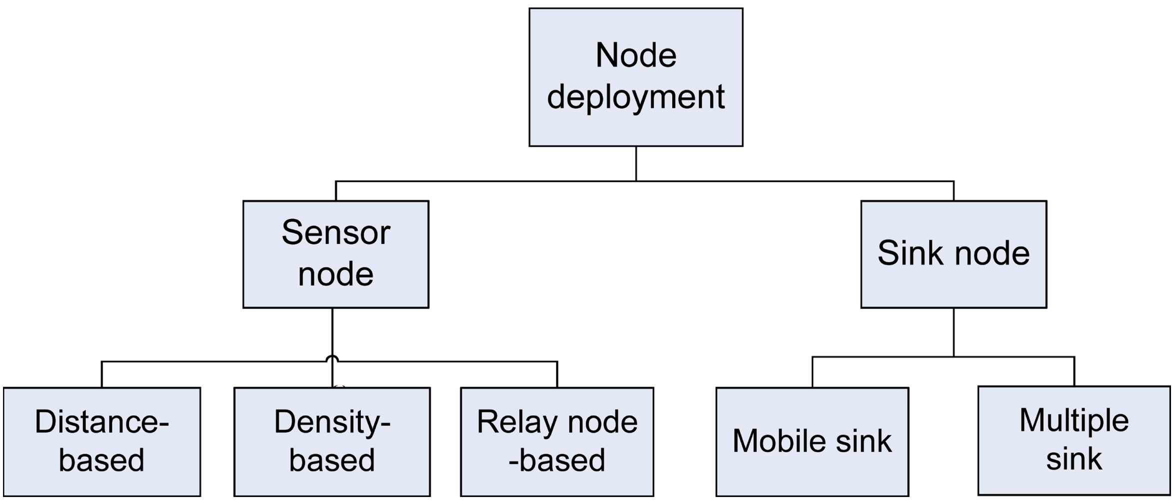

Figure 6. Classification of ECB node deployment mechanisms.

density-based deployment schemes, are proposed to balance the energy consumption of sensor nodes.

Initially, authors consider $N \times N$ grid-based WSN and propose topology construction to construct a balanced tree. The constructed tree guarantees root-balanced property that the total number of nodes in left subtree and right subtree of the sink node differ at most by one (see Figure 7 [15]).

After a tree is virtually built by the sink node, the sink estimates the number of forwarding packets required by each sensor according to its position in the tree. In Figure 7, the number labelled on each node denotes the number of forwarding packets at that node. The number of forwarding packets will help evaluate the power consumption for all sensor nodes. According to load, distance is estimated through any pair of nodes in the root balanced tree and this is the main theory of distance-based scheme. Sensor nodes use transmission power control which is regulated based on distance.

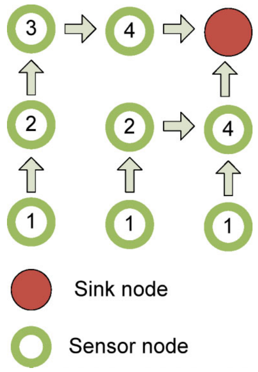

Figure 7. A 3 × 3 grid-based WSN. A root-balanced tree is constructed [15].

3.1.1.2. Density-based For density-based scheme, firstly, the whole monitoring area is partitioned into a number of equal-sized zones. Density of sensor nodes in each zone is adjusted based on the load. In a zone, one of the sensor nodes stays in active mode in turn and the other sensor nodes stay in sleep mode. Therefore, sensor nodes in the higher density zone will have more opportunity to sleep to achieve the goal of energy balance (see Figure 8 [15]). Compared to the distance-based scheme, the transmission power in the density-based scheme is fixed.

In order to adapt the schemes from grid based WSN to a randomly deployed WSN, authors combined two techniques together. Similar to density-based scheme, network area is partitioned into equal zones and active/sleep mechanism is used in order to balance the energy consumption. Since nodes are randomly deployed, density can be higher or sparser in the zones. In the zone where node density is higher than required one, power control mechanism will be applied by distance-based scheme. Utilising sensor nodes in a high-density zone to relay data packets will decrease the load of sensor nodes in a low-density zone, and therefore balance the energy consumption of each sensor in a randomly deployed WSN.

Another density-based mechanism is proposed in Reference [21]. Authors analyse communication load among nodes and then propose node distribution algorithm for deploying nodes. Algorithm divides network into rings and sink located in the centre of the first ring. Then, it determines the load in every ring and relative node density to it. The densities of sensor nodes are determined by solving an optimisation problem which maximises the coverage percentage.

3.1.1.3. Relay node deployment Examples of relay node deployment mechanisms are given in References [19, 20]. In Reference [20] authors proposed to deploy some heterogeneous sensor nodes which are more powerful than other nodes in terms of energy and computational capacity along with ordinary sensor nodes. Since these powerful sensors will be cluster heads, energy consumption among ordinary nodes can be balanced. Further to balance energy consumption, network area is divided into several small cells, and adjacent cells are filled with different colours–white or black. After sensor deployment, only powerful sensors in white cells are active and powerful sensors in black cells are turned off. Each ordinary sensor selects the closest powerful (in white cells) as the cluster head, and this leads to the formation of Voronoi cells. When powerful sensors in white cells run out of energy, powerful sensors in black cells wake up and form a different set of clusters in the network. By changing set of clusters, energy consumption balancing can be achieved.

Authors in Reference [19] proposed to use the strategy of the proper initial energy assignment (IEA) instead of using the uniform initial energy assignment. The main idea for the IEA strategy is to assign the energy level to node according

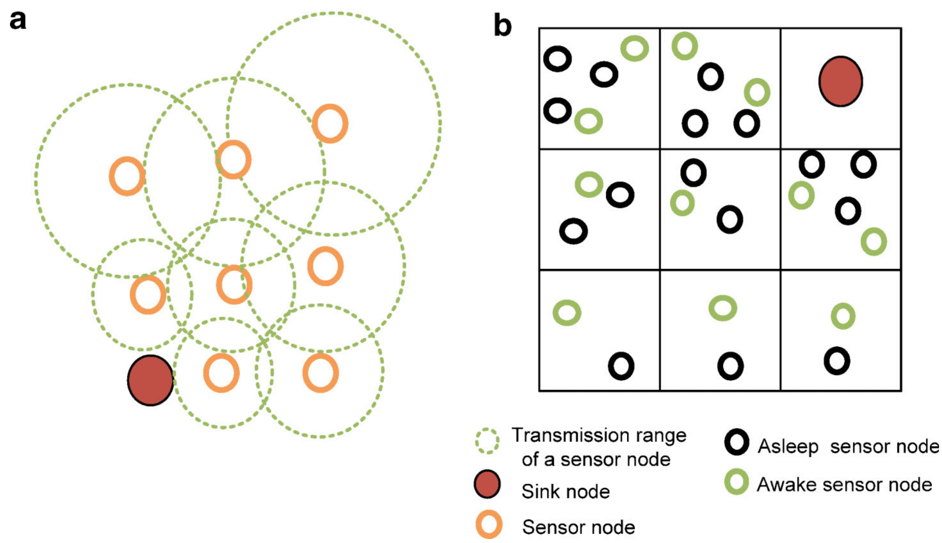

Figure 8. (a) The distance-based mechanism, (b) the density-based mechanism [15].

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to energy consumption as well as location of the node. The location and energy level of the sensors are given optimal load balance hence prolonging the network lifetime. It is assumed that the network area is circular and sink node is placed in the centre of the circle. The network area is divided into circles in which nodes are assigned different energy levels. The maximum energy level is assigned to nodes which are located in the first circle, i.e. the one nearest to sink node. The nodes that are closer to the sink should have higher power level; and the nodes that are further away from the sink should have lower power level.

3.1.2. Sink node options.

Sink node position regulates communication flow in WSNs. From this point of view, ECB issues might be severe where network has one sink node and data reported periodically. To mitigate this problem, sink node deployment mechanisms were proposed. Simply, deploying more data sinks in different positions or mobile sink node can mitigate the problem of unbalanced load. So, we can categorise the sink node approaches into two groups: mobile sink and multiple sink deployment [22–25] as shown in Figure 6. The main issue with mobile sink option is to determine mobile sink movement trajectory so that energy consumption of sensors is balanced and network lifetime maximised. The core issue for multiple sink is to determine energy balancing routing paths and optimal sink locations.

3.1.2.1. Mobile sink In Reference [22], optimal movement of mobile sink is investigated in a given heterogeneous WSN. The network comprises N sensors randomly deployed for periodic monitoring of an area and M sinks with mobility capabilities. The objective of the algorithm is to design the sinks' movements to balance the sensors' energy consumption. The case when sinks move on a predetermined path along a hexagon perimeter is addressed. Also, a distributed and localised algorithm for sinks' movements is proposed. This study shows an improvement of up to 4.86 times in network lifetime. Another mobile sink moving scheme is proposed in Reference [25] to attain ECB. Authors proposed two different schemes. In the first scheme, the sink directly moves to the sides of the node with the highest residual energy in the network to consume its energy. This scheme can be employed in small-scale and large-scale networks where sinks can move quickly. In the second scheme, the sink tends to move towards the node with the highest residual energy step-by-step, meanwhile avoiding passing by the middle nodes with low residual energy on the moving path. This scheme is more suitable for the mobile sinks that have limited move speeds. Both moving schemes can help sensor nodes consume their energy more evenly.

3.1.2.2. Multiple sinks In Reference [24], the problem of sink node positioning and route path finding is studied. The objective of this paper is to find the upper boundary of network lifetime for static network by mathematical framework. Three schemes are introduced to maximise network lifetime: k-Partitioned Minimum Depth Tree (k-PMDT), Mixed Integer Linear Programming (MILP) formulation and MILP heuristic algorithm. Each algorithm gives solution for positioning multiple sink nodes and for finding routing paths. The result of network lifetime by k-PMDT is the best compared to other algorithms (MILP and its heuristic). MILP is formulated to find the optimal solution. However, it is inappropriate to apply it to a large-scale sensor network because MILP is known to be NP-hard. Thus, heuristic algorithm for MILP formulation, which gives a near-optimal solution in polynomial time, is proposed by the authors.

In Reference [23], authors proposed system architecture of multiple-sinks and relative routing algorithms. Namely, two routing algorithms ELBR (Energy Level Based Routing) and PBR (Primary Based Routing) are proposed. The basic idea in ELBR is to calculate the energy level of the path then select the maximum energy level path to transmit data. The second routing scheme–Primary Based Routing considers both the energy level and the energy cost of the routing path so the energy consumption is balanced and the network lifetime is more prolonged.

Although proposed schemes in sensor and sink node deployment mechanisms vary depending on WSN type and network configuration, the key principle in these schemes are similar. For instance, some authors consider WSN clustered network or grid based network. Hence, depending on the assumption or consideration, schemes are different. In Table II, we describe and compare these mechanisms. We compare them in terms of degree of applicability, energy efficiency and global ECB based on their basic formulation. Since deployment mechanisms require special deployment scheme and additional requirements, it is reasonable to compare mechanisms in terms of applicability degree. Energy efficiency also is important and essential factor to be considered in WSN. In this respect, each mechanism design in WSNs should be energy efficient. Global ECB in table shows how each mechanism can provide ECB over the network. Notion of Global ECB means how much the mechanisms can provide ECB over network.

As we can see in the Table II, degree of applicability of mechanisms is low due to their special deploymental strategy requirements. For instance, the requirement in density or distance-based mechanism is to deploy nodes in predetermined manner, which might not be feasible in many applications. Further, financial cost can be high for these mechanisms [17]. We rated degree of applicability of mobile sink based mechanism 'very low' since few applications can support it. Respectively, energy efficiency of the mechanisms is compared in general. Generally, energy efficiency is not affected by mechanisms except distance-based mechanism. For node further from BS or for more load zone communication, distance also increases which causes energy inefficiency. Finally, although applicability of the mechanisms is low, they provide generally high global ECB.

Table II. General comparison of node deployment mechanisms.

Mechanism	Type of mechanism	Core concept	DA	EE	G-ECB	Comments
Sensor node deployment	Distance based[15]	Distance between deployed nodes is smaller when load is more. By consuming less energy in smaller distance, load is balanced.	L	L	H	If network area is large, the mechanism may not be feasible or energy efficient. For a node further from BS, communication distance will be large.
	Density based[12, 13, 15]	Deployment of node density is higher where load is more.	L	M	H	To tackle the energy imbalance, number of nodes can be very large. Accordingly cost of the network will be high.
	Relay node based[19, 20]	Deployment of some powerful nodes with ordinary nodes either randomly or in a predetermined manner.	L	H	H	Contrary to the above mechanisms, relay node based method can reduce node numbers significantly. However, it is costly since it requires special nodes for deployment.
Sink node deployment	Multiple sink based[23–25]	Deployment of multiple sinks in order to distribute load equally among nodes.	L	M	M	Although mechanism assists to distribute communication load well, it is application dependent.
	Mobile sink based[22]	Deployment of either several or single mobile sink node. The mobile node moves among sensor nodes so that energy level of sensors is equal in average.	VL	H	H	Since sink node moves around the network, nodes does not need to send data over a long distance which is much more energy efficient. However, disadvantage of the mechanism is that it is not feasible in many applications.

DA, degree of applicability; EE, energy efficiency; G-ECB, global ECB; L, low; M, medium; H, high; VL, very low.

3.2. Load balancing mechanisms

Load balancing mechanisms aim to distribute communication load among sensors by different means and in different communication layers so that energy consumption of sensors is balanced and network lifetime is prolonged. The load balancing mechanisms can be divided into following 4 categories (as shown in Figure 5).

3.2.1. Clustering.

Grouping nodes into clusters is widely studied by the research community. Every cluster has cluster head (CH) which gathers and aggregates data from cluster members and sends it to BS. Clustering has been shown to be effective approach for organising the network into a connected hierarchy. Furthermore, it has been shown that clustering prolongs the network lifetime significantly [6, 26]. One of the objectives of clustering is load balancing [27]. Load balancing objective can be of two types: intra and inter-cluster load balancing. In intra-cluster load balancing, node number or density is distributed equally in each cluster. In inter-cluster load balancing, communication load is distributed by different ways so that cluster head (CHs) can consume energy equally. Since CHs utilise multihop communication to send data to BS, unequal distribution of communication load among CHs arise.

Several unequal clustering methods are proposed in the literature [28–31] to tackle the problem of unequal communication load among CH. The basic theory of all proposed schemes is similar, that is, the clusters that are nearer to sink should have smaller size so that CHs in these clusters can balance their high energy consumption by communicating in a smaller distance between them (see Figure 9). In Reference [29] unequal clustering algorithm is proposed. Initially, several tentative CHs with the same probability T are selected. Each tentative CH broadcasts in the range *R0 com*p about its residual energy and competition range *Rcomp* which is a function of node's distance to BS. *R0 comp* is the predefined maximum competition range. Then, every tentative CH competes to be CH if there is one more tentative CH in its competition range *Rcomp*. The node having higher residual energy will be CH and in case of tie, node with smaller ID will win and be CH. In addition, authors introduced threshold TD_MAX in multihop forwarding model. If a node's distance to the BS is smaller than TD_MAX threshold, it transmits its data to the base station directly; otherwise it should find a relay node which can forward its data to the base station.

Another unequal clustering method is proposed in Reference [30]. In this clustering algorithm, cluster radii are determined based on energy consumption of CHs. Since cluster radius determines the communication distance between CHs and volume of data packet, each CH's energy consumption for receiving and relying can be estimated. Firstly, minimum and maximum cluster sizes are decided based on network parameters. Minimum cluster sizes are

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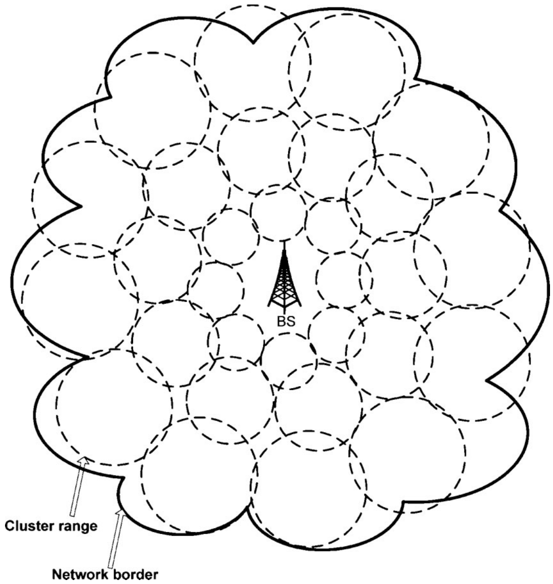


Figure 9. Conceptual figure of unequal clustering.

formed next to BS whereas maximum in the furthest location from BS. To estimate next layer of cluster size, the first layer cluster size (maximum) is subtracted from last layer cluster size (minimum). After second layer cluster size is estimated, next layer cluster size is determined based on energy consumption of second layer CH for receiving and relying data from first layer plus its data. By this way, each layer cluster size is determined. This algorithm may accurately balance the load between CH, since it is formed based on energy consumption of CHs.

In general unequal clustering algorithms cannot provide full ECB due to many to one traffic pattern nature of WSN [16, 12]. Although clustering cannot result in full ECB, it is good method to prolong network lifetime and balance load. The proposed algorithms mainly deal with one type of network in which a single sink is presented and a network area is circular. Unequal clustering algorithms can be extended to different network parameters such as multiple sink node or mobile node etc.

3.2.2. ECB routing.

Routing protocols is one of the most pursued research areas in WSN. Since main objective of WSN is to gather or acquire data from environment, to find energy efficient and energy balancing path to send that data is a task of routing protocols. Ideal routing algorithms should consider not only energy efficiency, but also the amount of energy remaining in each sensor, thus avoiding non-functioning sensors due to early power depletion [32].

In Reference [32] energy efficient and ECB routing protocol is proposed. The proposed routing algorithm uses a path with energy sufficiency as well as energy efficiency to attain energy balance. By using a composite of both quantities, a good path that achieves energy balance can be achieved. The definition of the composite measure, energy cost (EC_{ij}), for a transmission from node i to j is [32]:

$$\mathrm{EC}_{ij} = \frac{\text{Required energy from node } i \text{ to } j}{\text{Available energy at node } i} \tag{3}$$

So nodes will choose path which have minimum EC. The sensor determines among its neighbours and itself which sensor is the best candidate for direct communication with the base station. In order to determine this, sensor considers the total required energies to the base station via neighbouring nodes. The total energy cost (TEC_{ik}) of a neighbouring node k at senor i is simply the sum of the energy costs from node i to k and from node k to the base station [32]:

$$\mathrm{TEC}_{ik} = \mathrm{EC}_{ik} + \mathrm{EC}_{k,\mathrm{BS}} \tag{4}$$

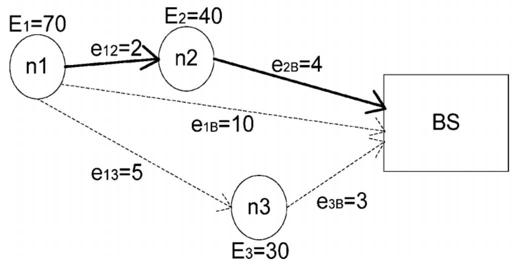
Based on this metric, sensor i can select the best candidate, node K, for direct communication with the base station:

$$k = \underset{jNi+\{i\}}{\text{Arg min}}(\mathrm{TEC}_{ij}) \tag{5}$$

By above estimation, decision is made to choose the best candidate which is energy efficient and balancing. Equation (1) helps to find a node with low energy cost and more residual energy. Equation (2) determines overall energy cost to transmit data from the node through neighbour to the base station. By this way, the best candidate is selected. If the best candidate node is the node itself, it sends data to the base station and completes the routing process for the data. Otherwise, it forwards the data to the best candidate among its neighbouring nodes and that node then repeats the same routing process. This process continues until a node selects itself as the best candidate and sends directly to the base station. This localised decision-making process results in a monotonic decrease of energy cost over time because the best candidate can have an indirect path that is better than direct transmission. Each sensor makes its decision with the assumption that one of its neighbouring nodes sends data to the base station directly. The concept can be understood more clearly through given scenario below (see Figure 10). In this scenario, node n1 needs to send data to BS and there are three routes. Each route has its related weight and the best route among them is second one (n1→n2→BS) in terms of energy efficiency and balancing.

In Reference [33] balanced, fault-tolerant, energy-aware routing (WEAR) is proposed. The main concept of the WEAR protocol is to combine four factors, i.e. the distance to the destination, the energy level of sensors, the global location information, and the local hole information. These four factors together make the protocol a general routing protocol. Authors firstly analyse the basic requirements of routing protocols of WSN and show importance of the four factors mentioned above. Based on this, routing protocol is designed. The routing decision is made based on a heuristic named weight, which is the combination of the four factors.

(a)



(b)

Route	$EC_{j,BS}$	EC_{ij}	TEC_{ij}
n1→BS	10/70=0.7	-	0.7
n1→n2→BS	4/40= 0.1	2/70 = 0.029	0.129
n1→n3→BS	3/30=0.16	5/70 = 0.071	0.171

Figure 10. Example scenario to demonstrate routing algorithm: (a) node n1 needs to send data to BS; (b) three routes and the route through n2 is best candidate.

Weight is formally defined as follows [33]:

$$W_j = \alpha G_j + \beta L_j + \gamma \mathrm{RE}_j + \lambda Dj_d \quad (6)$$

where W_j is weight value of the *j*th sensor; L_j stands for the value of the local hole information of the *j*th sensor; G_j is the value of the global location information of the *j*th sensor; RE_j is the remaining energy of the *j*th sensor and D_{jd} is the distance between the *j*th sensor and the destination. α, β, γ and λ are four parameters denoting the significance of the four factors.

WEAR can work in two manners. In the first case, the routing is totally based on the value of the weight. When a sensor receives a message, it chooses the next step from its neighbour list with the smallest weight value and forwards the packet to it. Step-by-step the message is delivered from the source to the destination. In the other case, the routing has two modes; the greedy mode and the bypassing mode. In the greedy mode, there must be neighbours that are nearer to the destination than the current sensor. Then the current sensor forwards the message to the neighbour having the smallest weight value. If there is no neighbour closer to the destination than the current sensor, the routing enters the bypassing mode. In the bypassing mode, the routing follows the right-hand rule to forward the message until the message reaches a node that is closer to the destination than the location where the bypassing mode starts. The advantage of the protocol is that it considers holes in network. This is very important since energy holes is common phenomena in WSN.

In Reference [34] load balancing routing scheme is proposed. The problem of determining the set of routes to be used by each sensor node and the associated weights that maximise the network lifetime by energy consumption is studied. It is assumed that WSN is directed graph G (V, E). For each sensor node V, generated reports to the sink can follow one of the possible paths in the set of paths $|P(v)|$. Each path $p \in P(v)$ is associated a weight $w(p)$ such that [34]:

$$\sum_{p \in P(v)} w(p) = 1 \quad (7)$$

The vector $W(v) = (w(p))_p \in P(v)$ represents the fraction of utilisation of each path $p \in P(v)$ used by node v to the sink node to send data. Firstly it is developed as an analytical model to derive the energy $E(u)$ consumed by each node $u \in V$ per unit of time according to a given routing set W, that is set of vectors $(W(v))_v \in V$. After obtaining $E(u)$ for each node $u \in V$, following function is used to derive the optimal routing set W [34]:

$$\max_w T(u) = \min_w(\max_{u \in V} E(u)) \quad (8)$$

The main constraints in ECB routing protocols is overhead of message exchange. Since mainly all routing protocols require information of residual energy of neighbour nodes to choose ECB path, frequently updating this information causes energy inefficiency. So, there is research room to reduce overhead of exchange message.

3.2.3. Operation scheduling.

Operation scheduling is one of the energy efficient ways for WSNs. It can be implemented to achieve ECB by sleep scheduling and task assigning according to residual energy while keeping sensing area covered.

In Reference [35] energy balancing and energy efficient sleep scheduling is studied elaborately. Clustered WSN is considered and the scheme aims to evenly distribute the load of the sensing and communication tasks among all the nodes in the cluster. The scheme estimates sleeping probability of each node and it is chosen in such a way that as many sensor nodes as possible consume the same amount of energy, on average. To achieve this phenomenon, authors consider a node distance from cluster head and expected energy consumption to cluster head.

In Reference [36] a balancing energy aware sensor management protocol (BESM) on PEAS (Probing Environment and Adaptive Sleeping) for WSN is presented. BESM allots more sleep time to those nodes that have less energy by two methods, namely negotiation strategy based on energy and energy saving method of nodes on the edge.

Negotiation strategy based on energy: All nodes in BESM are in the sleeping state and they sleep for an exponentially distributed random time after initialising state. When a node wakes up and enters Probe state, it sends a probe message to its neighbours within a certain probing range. Energy value of probing node is added in probe message. Any active neighbour nodes within the probing range compare their own energy value to the energy value in probe packet when they receive probe message. If its energy value is more than its neighbour node, it sends reply message and keeps working. Otherwise, it does not send reply message and goes to Sleeping state again. It enters Probe state after a random time sleeping. If the probing node does not hear any REPLY message or receives positive vote, it starts working. Otherwise, it goes back to sleep again for another random time. Node enters the dead state if it fails or consumes all its energy.

Energy saving method of nodes on the edge: To save energy of nodes on the edge of region covered by WSN, the mean of random sleep time for each node is modelled in inverse proportion to their own neighbour count. As a consequence, nodes on the edge can have more time to sleep so that their energy is not exhausted quickly. This assists to balance energy consumption of other nodes.

In Reference [37] interesting ECB sleep scheduling scheme is proposed. Authors consider two things that are, role switching (either sensing to sensing forwarding or vice versa) and sleep scheduling which are based on probability of percolate. Percolate theory is used here efficiently to support nodes to be connected and to keep covering sensing area while switching their roles and giving chance for sleep to nodes. According to the theory, two probability values, i.e. percolation and critical probabilities, are defined. Percolation probability is for switching role and nodes switch their roles independently according to the probability p ($p > p_c$, p_c is the *critical probability*), which can be adaptive to the network density and the residual energy of each node. If node's percolation probability p ($p < p_c$), that is, percolation probability is smaller than critical probability then percolation probability is considered zero. Sleep scheduling is also based on probability method and node goes to sleep mode for a fixed time interval with the probability P_{adaptive}, depending on the network density in that local area and the node's neighbour status.

As presented above, ECB can be achieved by allotting more sleeping time to nodes which have less energy or more load. Generally, it is difficult to expect full global ECB from sleep scheduling or task assigning mechanism, since sleeping time is limited to save energy. The main constraint in such mechanism is coordination of sleep and operation time.

3.2.4. Topology and transmission power control.

3.2.4.1. Topology control Topology control is a technique which manages nodes' transmitting ranges dynamically, in order to generate a network with the desired properties while reducing the energy consumption of the node. These desired properties may include network throughput, network lifetime, and connectivity [38]. A topology construction technique deals with transmission power of the nodes, state of the nodes (active or sleeping), role of the node (clusterhead, gateway, regular) etc. [39, 40]. We investigate techniques which deal with node's management of transmission power of a node. These techniques aim to find node optimal transmission power so that power of node is used in efficient and balanced way.

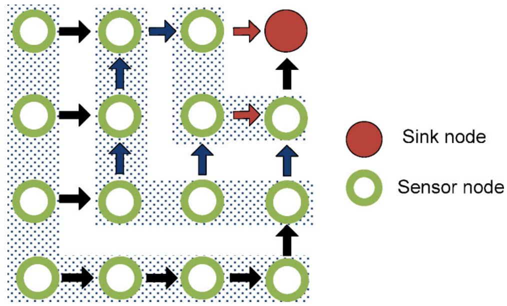


Figure 11. The shadow region marks the L-Layer partitions. A tree is constructed for a 4 × 4 grid-based WSNs [15].

In Reference [40] authors proposed an algorithm that optimally controls the topology for energy balanced consumption. The algorithm generates subgraph based on link weight which reflects the preference of using the link. The link weight is calculated as [40]:

$$W_{ij} = P_{ij} * W_i \tag{9}$$

where $W_i = M/E_i$, P_{ij} is power needed to transmit from node i to node j, M is the maximum energy (initial), E_i is remained energy of node i. The problem is to minimise the maximum power in each node such that largest edge (link) weight is the minimum.

In Reference [15] energy consumption balancing topology construction mechanism based on grid-based WSN is presented. The mechanism is called L-based that guarantees to construct the tree with root-balanced property in which total number of nodes in the left and right subtrees of the root differs at most by one. As shown in Figure 10 [15], sensors are divided into multiple L-layer. According to tree construction a right or up link will be established if the sensor is located in the odd or even L-Layer, respectively. The boundary sensors may be unable to transmit data packets to the sink node thanks to their location. Therefore, sensors located in the extreme top row will establish right links whereas sensors located in the extreme right column will establish up links (see Figure 11 [15]).

3.2.4.2. Transmission power control Although transmission power control and topology control are closely related terms, they are not same [38]. Transmission power control aims at optimising a single wireless transmission whereas concept of topology control is wider that it implies to control the topology of the graph representing the communication links between network nodes with different purpose [36]. Several studies have been done on optimising transmission power control to increase lifetime of network [10, 13, 16]. In Reference [13] authors tried to address the problem of transmission range distribution optimisation that determines what fraction of packets each node should send over each distance. The problem is solved by creating a probability density function (PDF) of the transmission range $p_i(d)$ for each sensor S_i. Initially, the total traffic being forwarded from sensor S_i to sensor S_j is $T(S_i, S_j)$ and the distance between S_i and S_j is $d(S_i, S_j)$. The transmission range PDF $p_i(d)$ of sensor S_i can be determined as [12]:

$$p_i(d) = \frac{\sum_{S_j:d(S_i,S_j)=d} T(S_i, S_j)}{\sum_{S_j \in S} T(S_i, S_j)} \tag{10}$$

Further, authors determine upper bound of network lifetime by linear programming. Simulation results of the work showed that energy inefficiency occurs when especially nodes in far field region send data on a longer distance to balance load in network. It is concluded that optimal distribution solely cannot solve the problem of energy imbalance because of energy inefficiency.

In Table III, we summarise and compare load-balancing mechanisms. Since all of the mechanisms are generally applicable without additional requirements besides topology construction, it is easy to deploy those mechanisms. Topology construction mechanism requires extra resource that sensor node should have capability of controlling power which may not be feasible always. Furthermore, Global ECB evaluation is low in all mechanisms due to many to one communication pattern which is unavoidable without deployment mechanisms [11, 13].

3.3. Energy mapping and monitoring mechanisms

Energy mapping mechanisms deal with producing picture of energy distribution in the network so that some preventive actions are taken [41–44]. Since energy mapping is associated with energy monitoring, in several studies they come together [41–44]. One of the potential gains of energy mapping mechanisms is that they can provide guidance to balance load by early warnings of network failure so that network lifetime is prolonged [41]. For instance, network manager is aware from energy map that energy of sensors in some part of the network is going to run out. Then he/she can reconfigure the network or deploy some additional sensors in that part of the network to prolong network lifetime. In this respect, energy mapping mechanisms can be considered as indirect ECB mechanism.

In Reference [42] authors proposed a hierarchical approach for collecting residual energy information in order to construct an energy map at the base station. Initially, an entire sensor network is divided into several static clusters using the TopDisc algorithm. Cluster head of each cluster and bridging delivery nodes between two adjacent clusters are part of topology tree. Each node in a cluster sends its energy information to cluster head of the cluster. The energy information includes the position of the node and the energy value. Cluster head divides all the nodes into several sets according to different energy ranges. A convex contour is generated for each node set, and only the vertexes and the

Table III. General comparison of load balancing mechanisms.

Mechanism	Core concept	DA	EE	G-ECB	Comments
Unequal clustering[28–31]	Distance between deployed CHs is smaller when load is more. By consuming less energy in smaller distance, load is balanced among CHs.	H	M	L	Although it might be energy inefficient, it has several advantages such as load balancing, high scalability etc.
ECB routing [32–34]	Choose optimal path by considering energy efficiency and available energy.	H	M	L	It is required to choose sometime longer paths to attain ECB. Hence, energy efficiency is considered medium.
Operation scheduling[35–37]	Allocating sleep and task time according to energy level.	H	H	VL	Although it achieves high-energy efficiency, it cannot provide high rate of global ECB because of limited sleep time scope.
Topology and Transmission power control[15, 39, 40]	Dynamically change transmission power of node to attain connectivity and ECB.	M	L	H	Since sensor node may be incapable of controlling transmission power, its applicability is considered medium.

DA, degree of applicability; EE, energy efficiency; G-ECB, global ECB; L, low; M, medium; H, high; VL, very low.

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sequence are stored. Boolean computing is applied between each contour. The result will be general contours; it can be concave, have holes, and be consisted of several parts. The topology tree is then used to collect the energy graphs from leaf nodes to the base station. Based on the collected energy information, a set of polygons which represent the contours of different energy levels is produced independently for each cluster. In addition to the construction of the initial topology tree for energy collection, reorganisation of the tree to evenly distribute energy consumption in the monitoring process is performed periodically to extend the battery life of the sensors in the network.

Another energy mapping and monitoring mechanism called forecasting-based monitoring and tomography (FMT) is presented in Reference [41]. The principle of FMT framework is to forecast available energy based on available energy history of a sensor. Since energy cost can be high for energy monitoring purpose (updating available energy information to map energy), instead of frequently updating available energy information, a sensor can forecast the energy depletion based on its observed available energy value. Energy information is sent to monitoring node only when difference between previous forecasted dissipation rate and current forecasted dissipation rate is higher than certain threshold. Then, using the energy dissipation rate, and the received available energy value, the monitoring node continuously updates residual energy of the sensor nodes. In order to perform accurate available energy forecasting, single parameter double exponential smoothing method is utilised. This method allows for removing the effects of obsolete data in order to forecast accurately. The method uses only the last portion of the data, for example, the last τ samples, and to give relatively more weights to the recent observations than the older observations.

Authors of Reference [43] approached the problem of energy mapping by mining the sensor data using nonlinear manifold learning algorithms. Using these algorithms, it is possible not only to visualise the energy distribution and location of each sensor in a network but also to find the dynamic patterns from a large volume of sensor network data. In the data mining procedure, the sample energy values of each sensor is collected and they are expressed as $X_i = \{x_i(1), x_i(2), \ldots, x_i(M)\}$ where Mth sample is collected from sensor i. In order to extract and visualise the energy distribution, a d dimension domain Y_i contained in an Euclidean space R^d from observations X_i in the observation space R^D is obtained. For inverting X_i to Y_i according to Iso-Map algorithm following framework is proposed by authors:

- In step 1, neighbourhood graph is constructed.
- In step 2, the shortest paths are computed.
- In step 3, 2-deminsional embedding is constructed in Euclidean space.

In Reference [44] authors proposed Iso-Map for contour mapping, which constructs contour maps based solely on the reports collected from intelligently selected 'isoline

Table IV. General comparison of energy mapping and monitoring mechanisms.

Approach	Core concept	EE	Acc	Comments
Gungor, V.C [41]	To forecast available energy based on available energy history of a sensor. Energy information is sent to monitoring node only when difference between previous forecasted dissipation rate and current forecasted dissipation rate is higher than certain threshold.	M	M	Simple technique to map energy but it may take a time for system convergence. Since to accurately forecast available energy based on available energy history, system needs time to collect available information.
Edward Chan *et al.* [42]	When CHs receive energy values, divide nodes into several sets according to energy levels. Convex contour is generated for each node set. Results are then sent to BS and BS produce a set of polygons which represent the contours of different energy levels.	L	H	Since it needs to collect energy value periodically, it may cause energy inefficiency and message overhead.
Song Ci *et al.* [43]	The sensor data is mined using nonlinear manifold learning algorithms.	L	M	The algorithm works only with mapping energy. Hence, it might cause energy inefficiency to collect energy information.
Yunhao Liu *et al.*[44]	Iso-Map algorithm constructs contour maps based solely on the reports collected from intelligently selected 'isoline nodes'.	M	M	The approach includes both energy mapping and monitoring. However, to choose correct 'isoline nodes' is critical. The energy mapping and monitoring solely depends on these 'isoline nodes'.

EE, energy efficiency; Acc, accuracy; L, low; M, medium; H, high; VL, very low.

nodes'. In order to build contour maps in sink node, sink node disseminates a query through the routing tree over the targeted field. The query message includes the data space $[v_L, v_H]$ and the granularity T of the contour map, which specifies the desired isolines in the contour map with the isolevels $vi = v_L + i \cdot T \in [v_L, v_H]$. Each sensor node determines whether it is an isoline node based on the following:

- sensing value of a node is within a predefined border region of the isolevel vi specified in the query, $[vi - \varepsilon, vi + \varepsilon]$;
- One of its neighbouring nodes q has a sensing value vq, where vi is between their sensing values, i.e. $vp < vi < vq$, or $vq < vi < vp$.

So, if sensor node satisfies the above conditions then it is considered isoline node. Each isoline node generates a 3-tuple report $r = < v, p, d >$, in which v represents the isolevel of the node, p represents the position of the sensor node and d represents the gradient direction of the attribute value at the sensor node. When sink node receives isoline node reports, it constructs the contour map which is delineated by isolines of different isoleve. The sink separately constructs isolines of different isolevels, and the contour regions reside between them.

Above we presented some approaches on energy mapping. The main constraint on mapping is to collect residual energy of a sensor periodically which causes energy inefficiency and message overhead. Hence, some authors proposed methods to reduce the number of reports. Although these methods decrease the number of reports significantly, there is tradeoff between mapping accuracy and number of reports [41, 44].

We presented above some examples of energy mapping and monitoring mechanisms. The main constraint in these mechanisms is to update available energy information and accuracy of produced energy map. Hence, researchers attempted to decrease amount of information message by different approaches as we discussed earlier. Energy mapping mechanisms have big potential to monitor the condition of a network and to take preventive actions like node predeployment, task assignment etc. The Table IV shows the comparison of above presented energy mapping and monitoring approaches in terms of energy efficiency and accuracy. Depending on the periodic energy report, energy efficiency is measured.The frequent energy report may provide accurate energy map; on the other hand, it causes message overhead and energy inefficiency. Hence, as it is demonstrated in the table IV some of the algorithm can provide more accurate energy map but it is not much energy efficient. So there is trade off between energy efficiency and map accuracy.

4. CONCLUSION

This paper provides review of energy consumption balancing (ECB) issues in wireless sensor networks (WSN). To give better understanding of ECB, first, overview of ECB and ECB related factors were explained. We showed that main reason for energy imbalance is unequal distribution of communication load. Second, an extensive literature survey is presented by summarising and categorising the recent and state of the art ECB mechanisms. We categorised ECB mechanisms into three categories: node deployment, load balancing and energy mapping. Although node deployment mechanisms can provide high rate of global ECB, degree of applicability of these mechanisms is low in general. On other hand, load balancing mechanisms are limited in providing global ECB although degree of applicability of these mechanisms is high in general. The main reason for this issue is many to one communication nature of WSNs. Hence, node deployment mechanisms are proposed to tackle the problem. Moreover, energy mapping ECB mechanisms are presented. We stated the main constraints of the ECB mechanisms and compared them in different terms. For further research on ECB, we recommend for developing a framework for ECB and for evaluating factors affecting ECB mechanisms. Further we showed some constraints of the mechanisms in Section 3, which should be addressed. We hope that this survey will be helpful and useful for those pursuing research in ECB mechanisms.

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