

Article

Novel Reliable and Energy-Efficient Routing Protocols for Wireless Sensor Networks

Mohammed Almazaideh * and Janos Levendovszky

Department of Networked Systems and Services, Budapest University of Technology and Economics,
1111 Budapest, Hungary; levendov@hit.bme.hu

* Correspondence: almazaida@hit.bme.hu; Tel.: +36-40-215-3964

Received: 28 November 2019; Accepted: 4 January 2020; Published: 8 January 2020



Abstract: In this paper, novel energy-aware and reliable routing protocols are proposed. The aim is to maximize the lifespan of wireless sensor networks (WSNs) subject to predefined reliability constraints by using multi-hop routing schemes, in which the source node forwards the packet to the base station (BS) via other nodes as relays. In the first proposed protocol, energy efficiency is achieved by maximizing the minimum residual energy of the path subject to fulfilling a predefined reliability constraints. The second protocol is an optimized version of the first one with respect to lifespan and complexity. The optimal path is the one in which the residual energy distribution of the nodes along the path is as close to uniform as possible and the packet arrives at the base station with a given success probability. To measure the uniformity of the residual energy distribution, we use an entropy like measure. The information about the current energy state of the network is maintained by using a look-up-table from which the optimal routes are computed on the BS. The BS broadcasts the updated optimal paths to each node after each round of packet transmission.

Keywords: WSN; residual energy; routing protocols; entropy of energy; energy efficiency

1. Introduction

A wireless sensor network (WSN) is a distributed system consisting of several nodes, and one or more base stations (BS). The nodes are typically small and cheap. BS's have higher processing capabilities and a wired electrical power source. The sensor nodes are equipped with application-specific sensors and a mini central processing unit. There is also a wireless radio transceiver attached to each sensor node; it provides the node with the capability to communicate with each other and with the BS. These nodes often operate on their battery power and use unreliable radio channels corrupted by noise and fading. As a result, the primary concern, when designing and operating such a network, is to maximize the life span and the data throughput of the nodes [1].

Packets are sent to the BS either in a single-hop manner or in a multi-hop manner. In case of single hop, the node sends the generated packet directly to the base station, wherein a multi-hop manner, source nodes send packets to BS via multi-node path, each node of the path forwards the received (or, in the case of the source node, the generated) packet to another node until the BS receives the packet [2]. Packets are transmitted to the BS via unreliable radio channels corrupted by noise and fading [3].

Many techniques have been developed to increase the energy efficiency of WSNs, covering almost all layers of communication protocols ranging from the physical layer to the application layer [4,5]. Routing is instrumental when designing and operating WSNs; the researchers in [6] describe a group of routing metrics and constraints; they provide a guideline for the composition of these metrics to achieve efficient routing schemes.

Load balancing and reliable information transfer are contributory factors in energy-efficient communications. Lack of load balancing causes the death of some nodes too early, which breaks the

connectivity of WSN and reduces the life span of the WSN [7]. The lifespan is defined as the length of time interval until the first node goes flat [8].

The reliability in WSN categorized into three classes: packet reliability, event reliability, and packet-event reliability. In this paper, we focus on packet reliability. It is classified to up-stream packets, (which mostly represents data packet), and down-stream packets, (which generally represent control packets) [3]. Low reliability leads to high packet loss ratio in the case of low energy consumption. Most protocols achieve energy efficiency by enforcing uniform energy distribution and maximum longevity, but they do not provide reliable links where lost data means wasted energy. Also, they don't use distinct measure for the uniformity of residual energy distribution.

In this paper, we try to strike a good balance between reliability and energy consumption (longevity). Our concern in the first part of this paper is to develop novel routing algorithms that maximize the minimum residual energy subject to a predefined reliability target. To achieve this, we propose the Maximum of the Minimum Residual Energy Protocol (MMREP). According to the proposed method, we select a path by which a packet is sent to the BS over the nodes, of which the minimum remaining energy is the maximum subject to the reliability constraint. The reliability constraint means that the packet will reach the BS with a given probability. This strategy can significantly extend the life span of WSNs.

In the second part of this paper, we improve the performance of the basic MMREP in terms of energy efficiency and complexity. We propose an Optimal Residual Energy Based Protocol (OREBP). In OREBP, we use the entropy-like function to measure the uniformity of the residual energy distribution. The packets are sent to the BS in a multi-hop manner. The protocol guarantees that the distribution of the residual energy will remain as close to uniform as possible. We will demonstrate that this method achieves optimal load balancing.

In this paper, we introduce two novel routing algorithms. They achieve an efficient load balancing under predefined reliability constraint. The key contributions of this paper are summarized as follows: First, we presented a mathematical analysis for the selection of relay nodes based on the remaining energy and reliability. Second, we proposed MMREP to select the path that maximizes the remaining energy of its nodes subject to the reliability constraint. Third, we introduced the entropy-like function to measure the uniformity of residual energy distribution. Fourth, we proposed OREBP, which selects the path based on the entropy of residual energy of the path.

The remainder of the paper is organized as follows:

- In Section 2, we provide an overview of related work in the literature.
- In Section 3, we introduce the framework in which the different communication protocols will be discussed.
- In Section 4, we describe MMREP to select the path which keeps the residual energy as maximum as possible.
- In Section 5, we describe OREBP to select the optimal path that maintains uniform residual energy distribution.
- In Section 6, we give the numerical results of a detailed performance analysis of the algorithms where their performances are compared with other protocols.
- In Section 7, some conclusions are drawn, and remarks on future research directions are given.

2. Related Work

Previous works were done in the field, classify energy-efficient routing protocols into homogeneous WSN protocols (where all the nodes are identical) and heterogeneous WSN protocols, where both are subdivided into static and mobile [9]. Other researchers classify them based on network structure (flat and hierarchical); communication model (negotiation-based, query-based, and coherent-based); topology (location-based and mobile agent-based); and reliability (QoS-based and multipath-based) [10].

Some researchers improved the energy efficiency of WSN by using hierarchical packet forwarding protocols. Low Energy Adaptive Clustering Hierarchy (LEACH) is a hierarchical cluster-based protocol. The network is divided into several clusters; a cluster head (CH) is selected to receive the packets from respective members of that cluster, and then, it forwards the packet directly to the BS. In LEACH, energy efficiency is achieved by clustering and data fusion. By clustering, just the CH has a direct long-distance transmission to the BS; other nodes send their data to CH in short-distance transmission. By data fusion, the CH removes redundant data and fuses the received packets into a single packet. The cluster heads are selected randomly and changed periodically in time to achieve load balancing [11]. However, ignoring the energy level of the cluster head may make it a bottleneck node, and it does not consider reliability.

There are several modified versions of LEACH, these modifications based on three titles, selection of CH, clustering, and data transmission. In LEACH-C, the selection of CH is centric and performed by BS based on the remaining energy and location of nodes [9]. In NEAHC, load balance and energy efficiency are achieved by selecting the CH based on remaining energy. Also, members with low energy are forced to switch between sleep and active status [12]. The authors of [13] propose the selection of CH and clustering based on practical swarm optimization and fuzzy logic; the fitness function depends on the distance between nodes and CH, the distance between CH and BS, and the minimum consumed energy. In [14], the firefly heuristic algorithm is used to select the CH based on distance, energy, and delay. In terms of clustering, CACD algorithm constructs clusters based on the energy depletion of the clusters and node density [15].

PEGASIS is an underlying chain-based routing protocol [16], it is a modification of LEACH, the nodes are grouped into a chain using a greedy algorithm, and each of them acts as chain head in turn; each node fuse the received packet into its packets, the fused packet is forwarded to the closest neighbor until it arrives at the chain leader. The chain leader aggregates the packets together and sends them directly to the BS. By selecting the chain leader, regardless of its energy, can result in a shorter lifespan. CHIRON [17] is a chain-based routing protocol that increases energy efficiency by dividing the network field into some smaller areas to create shorter chains for reducing data transmission delay and path duplication. The Energy-Efficient Chain-Based (EECB) routing protocol [18] modified PEGASIS by selecting the chain leader based on the residual energy and distance from the BS. The scheme in [19] selects the chain leaders from a group of nodes in the neighborhood of BS. The authors of [20] used a heuristic Ant Colony optimization to reduce delay and to find the optimal path with minimum transmission distance.

Regarding the reliability, in [8], an energy-efficient and reliable protocol is proposed, predefined reliability is achieved by multipath routing. But, only two-hop paths are assumed. Researchers of [21], improve the reliability by finding the best location of CH. RE-AEDG [22] and GIN [23] protocols use the cooperative routing model to enhance reliability, where the transmitted packet is overheard by several neighbors and retransmitted by several neighbors too. Some researches use network coding to improve reliability [24,25]. Most of these protocols improve reliability by increasing the redundant data, which means wasted energy.

These protocols, however, do not achieve optimal energy balancing, and do not take the reliability into consideration when selecting an energy-efficient path. As a result, further investigation is needed into developing packet forwarding mechanisms.

3. The Model

WSNs consist of a number of nodes which are deployed randomly in a sensing field. The network is represented by a graph $G(V, E, d)$, where set V refers to the nodes $N = |V|$, while set E denotes the edges and d_{ij} , ($i, j = 1, \dots, N$) are the distances between the nodes, which are arranged in a distance matrix, and the distance represents the weight of the corresponding edge. Packets are forwarded from the nodes to the BS in the form of multi-hop routing. In multi-hop protocols, the nodes use each other to relay the packets until packet is finally received by the BS.

Based on the Rayleigh fading model [18], the energy g_{ij} needed for transmitting a single packet over distance d_{ij} with the probability of successful transmission between node i and node j denoted by P_{ij} is given as:

$$g_{ij} = -d_{ij}^\alpha \frac{\theta \sigma_Z^2}{\ln(P_{ij})} \tag{1}$$

where θ is the so-called modulation and coding constant [26], σ_Z^2 denotes the power of noise, α is the large-scale path loss exponent (usually $2 \leq \alpha \leq 6$).

The reliability constraint is expressed by a predefined data loss percentage ε ; where the probability of overall success of packet transmission from the source node to the BS is supposed to fulfil $\prod_{j=0}^m P_{l_j l_{j+1}} = 1 - \varepsilon$, in case of using m relay nodes to forward packets to the BS. We adjust g_{ij} to get same P_{ij} for all nodes, then $P_{ij} = \sqrt[m]{1 - \varepsilon}$.

The energy of the network at time k is described by an energy state vector $c(k) = (c_1(k), \dots, c_N(k))$ where $c_i(k)$ represents the available battery power at node i at time instant k . We assume that all the nodes have the same initial energy at time instant 0, i.e., $c_i(0) = EV$, $i = 1, \dots, N$. When seeking a path for a maximum m relay node from the source node s to the BS, we search for a set of indices $R = \{l_1, \dots, l_m\}$ referring to the relay nodes participating in the packet transfer, where the first source node, s , sends the packet to node l_1 then the packet is forwarded to node l_2 and so on, and finally from node l_m to the BS. Each node has a copy of the routing table which is calculated and broadcasted by the BS.

In the forthcoming discussion, we assume that the BS has full information on the distance matrix of the network and, as a result, it has the routing table of all nodes. The BS updates its version of the energy state vector after receiving each packet, by which it perceives of the remaining energy and the existence of the nodes. With each round, it runs the proposed algorithms to calculate the optimal path from each node according to the energy state vector, the predefined data loss percentage (ε), and predefined maximum number of hops. The updated routing table is then broadcast to all nodes. We also suppose deterministic transmission, where the nodes transmit the same amount of data in a predefined frequency (periodically), and each node forwards packets according to its routing table.

One may say that this procedure will increase the energy consumption due to the frequency of BS broadcasting. However, the energy needed for receiving is significantly less than the energy needed for transmission [15]; it does not depend on the distance; it just depends on the size of the received information. The information received by the nodes is a short control message; it consists of the ID of the node, the ID of the next relay node, and the ID of the source node. Moreover, nodes eliminate the overhead required for chain or path setup, as with PEGASIS and LEACH [8,15]. The BS, with its high energy and high computational capabilities, does all the work—this configuration is used for the majority of IoT systems. Besides that, the proposed algorithms reduce the consumed energy in overhearing reception; the node receives just from the relay node specified by BS deterministically, which makes the algorithms beacon-less because the nodes don't need to exchange routing information.

In the proposed protocols, aside from the necessity of determining the optimal energy consumption values that maximizes the residual energy of the path, it is also necessary to guarantee that the packets arrive at the BS with a given reliability $(1 - \varepsilon)$.

4. Maximizing the Minimal Residual Energy

In this section, we select a path by which a packet is sent to the BS with the minimum remaining energy is maximum subject to the constraint that the packet will reach the BS with a given probability.

Thus, the path over which the packet is forwarded to the BS (denoted by \mathfrak{R}) is optimal if:

$$\mathfrak{R} : \max_{\mathfrak{R}} \min_i c_i(k + 1)$$

subject to the constraint $\prod_{j=0}^m P_{l_j l_{j+1}} = 1 - \varepsilon$. This strategy can be implemented when the hop count of packet transfer has been set prior to sending the packet to the BS.

4.1. Two-Hop Routing

Let us assume that packets are forwarded to the BS in a two-hop path, and the sender node is denoted by s , while the intermediate node relaying this packet to the BS is denoted by l . Then, there are two components that change in vector $c(k + 1)$ compared to $c(k)$,

$$c_s(k + 1) = c_s(k) - \left(-d_{s,l} \frac{\theta \sigma_Z^2}{\ln(P_{sl})} \right) \quad (2)$$

and

$$c_l(k + 1) = c_l(k) - \left(-d_{l,BS} \frac{\theta \sigma_Z^2}{\ln(P_{l,BS})} \right) \quad (3)$$

Furthermore, to ensure that the packet sent by node s reaches the BS with a given probability $(1 - \varepsilon)$, then the reliability constraint can be expressed $P_{s,l} * P_{l,BS} = 1 - \varepsilon$. Thus, in the case of two-hop routing, one can determine the relay node l , by solving the following constrained optimization problem:

$$l_{opt} : \max_{l} \min \left\{ c_s(k) - \left(-d_{s,l} \frac{\theta \sigma_Z^2}{\ln(P_{sl})} \right), c_l(k) - \left(-d_{l,BS} \frac{\theta \sigma_Z^2}{\ln(P_{l,BS})} \right) \right\} \quad (4)$$

subject to the constraint $\ln(P_{s,l}) + \ln(P_{l,BS}) = \ln(1 - \varepsilon)$.

Solution

Let us assume that we have chosen a relay node denoted by index l , then the condition $P_{s,l} P_{l,BS} = 1 - \varepsilon$ can be paraphrased as:

$$\ln(P_{s,l}) + \ln(P_{l,BS}) = \ln(1 - \varepsilon). \quad (5)$$

From Equation (1):

$$-\frac{d_{s,l}^\alpha}{g_{s,l}} \theta \sigma_Z^2 - \frac{d_{l,BS}^\alpha}{g_{l,BS}} \theta \sigma_Z^2 = \ln(1 - \varepsilon). \quad (6)$$

From Equation (6), we can define $\varphi(g_{sl})$ which expresses the relationship between $g_{l,BS}$ and $g_{s,l}$ due to the constraint as:

$$\varphi(g_{sl}) = g_{l,BS} = \frac{-g_{sl} d_{l,BS}^\alpha \theta \sigma_Z^2}{g_{sl} \ln(1 - \varepsilon) + d_{l,BS}^\alpha \theta \sigma_Z^2}. \quad (7)$$

The minimum residual energy (if node l is selected) will be maximum if the residual energy at the source node and the relay node are equal to each other, i.e., $c_s(k + 1) = c_l(k + 1)$. So, from Equations (2) and (3): $c_s(k) - g_{s,l} = c_l(k) - g_{l,BS}$ and by using Equations (6) and (7), we have:

$$c_s(k) - g_{s,l} = c_l(k) - \varphi(g_{sl}). \quad (8)$$

We can use Equation (8) to determine $g_{ls,opt} : c_s(k) - g_{s,l} = c_l(k) - \varphi(g_{sl})$. Since the source node s is given, we can calculate $g_{ls,opt}$ for all possible relay nodes $l = 1, \dots, N$. Then l_{opt} can be selected by solving the problem:

$$l_{opt} : \max_{l \in \{1, \dots, N, l \neq s\}} c_s(k) - g_{ls,opt}. \quad (9)$$

This requires the solution of (8) $N - 1$ times and then $N - 1$ comparison of the value $c_s(k) - g_{ls,opt} \forall l = 1, \dots, N, l \neq s$.

4.2. m-Hop Routing

Based on this reasoning, the protocol can easily be extended to m-hop routing as well. In this case, we assume that packets are forwarded to the BS via an m-hop path and the sender node is node $l_0 = s$ and the sink node is the BS denoted by $BS = m + 1$. The path containing the sender and the relay nodes is denoted by $\mathfrak{X} = \{l_0, \dots, l_m\}$.

Then, there are $m + 1$ components changing in vector $c(k + l)$ compared to $c(k)$, given as $c_l(k + 1) = c_l(k) - g_{l_j, l_{j+1}}, j = 0, \dots, m$. Similar to the previous constraint, if we want to ensure that the packet sent by node s reaches the BS with a given probability $(1 - \varepsilon)$, then the reliability constraint can be expressed as $\prod_{j=0}^m P_{l_j, l_{j+1}} = 1 - \varepsilon$.

Thus, in the case of m-hop routing, we have to solve the following constrained optimization problem:

$$l_{1opt}, l_{2opt}, \dots, l_{m-opt} : \max_{l_2, l_3, \dots, l_m} \min_{j \in \{0, \dots, L\}} \left(c_{l_j}(k) - \left(-d_{l_j, l_{j+1}} \frac{\theta \sigma_Z^2}{\ln(P_{l_j, l_{j+1}})} \right) \right) \quad (10)$$

subject to the constraint $\prod_{j=0}^m P_{l_j, l_{j+1}} = 1 - \varepsilon$.

Solution

Let us assume that we have chosen a path $\mathfrak{X} = \{l_0, \dots, l_m\}$. Along with this path, the reliability constraint $\prod_{j=0}^m P_{l_j, l_{j+1}} = 1 - \varepsilon$ can alternatively be given as $\sum_{j=0}^m \ln(P_{l_j, l_{j+1}}) = \ln(1 - \varepsilon)$.

From Equation (1) it becomes:

$$\sum_{j=0}^m \ln(P_{l_j, l_{j+1}}) = - \sum_{j=0}^m \frac{d_{sl_j}^\alpha}{g_{sl_j}} \theta \sigma_Z^2 = \ln(1 - \varepsilon). \quad (11)$$

The minimum residual energy will be maximum if the residual energy at all the relay nodes are equal to each other, i.e., $c_{l_j}(k + 1) = c_{l_{j+1}}(k + 1), j = 0, \dots, m$. So, from Equations (2) and (3):

$$c_{l_j}(k) - g_{l_j, l_{j+1}} = c_{l_{j+1}}(k) - g_{l_{j+1}, l_{j+2}}. \quad (12)$$

The $m + 1$ equations above yield a solution to $g_{opt} = (g_{l_0, l_1, opt}, \dots, g_{l_m, BS, opt})$. We can calculate g_{opt} for all possible m-hop paths by fixing the path $\mathfrak{X} = \{l_0, \dots, l_L\}$. Then the optimal path $\mathfrak{X}_{opt} = \{l_0, l_{1, opt}, \dots, l_{m, opt}\}$ can be sought by solving the following problem:

$$\mathfrak{X}_{opt} = \{l_0, l_{1, opt}, \dots, l_{m, opt}\} : \max_{\mathfrak{X}} c_{l_0}(k) - g_{l_0, l_1, opt}. \quad (13)$$

This requires the solution of (11) $\sum_{L=1}^m \frac{(N-1)!}{L!(N-1-L)!}$ times and then $\sum_1^m \frac{(N-1)!}{L!(N-1-L)!}$ comparisons of the value $c_{l_0}(k) - g_{l_0, l_1, opt}$. We will refer to this method of routing the packets to the BS as the maximum of minimum residual energy protocol (MMREP).

5. Optimal Path Selection Based on Energy Entropy

We can further generalize this method by introducing an entropy-like measure on energy distribution. The equality of residual energy of relay nodes can be extended for uniform distribution of residual energy across all the path's nodes. This uniformity can be achieved by maximizing entropy. At instant ($K = 0$), the entropy is maximum because all the nodes have the same initial energy; to keep the entropy at maximum, the gradient of the entropy should be minimized. We can calculate the entropy

of the normalized residual energy distribution on the nodes of the network $\bar{c}(k) = c_1(k), c_2(k), \dots, c_N(k)$ at time instant k . Hence, the entropy characterizing the current energy distribution is:

$$H(\bar{c}) = \sum_{i=1}^N \frac{c_i(k)}{\sum_{j=1}^N c_j(k)} \log \frac{\sum_{j=1}^N c_j(k)}{c_i(k)} \quad (14)$$

The gradient of the entropy can be calculated as follows:

$$\bar{V} = \nabla H(\bar{c}) = \left[\frac{\partial H}{\partial c_1}, \frac{\partial H}{\partial c_2}, \dots, \frac{\partial H}{\partial c_N} \right]. \quad (15)$$

Suppose that source node s is sending a packet via the relay nodes l_1, \dots, l_m where l_m is the last relay node, then the residual energy of nodes involved in packet forwarding will change as:

$$c_{l_j}(k+1) = c_{l_j}(k) - \left(-d_{l_j, l_{j+1}} \frac{\theta \sigma_Z^2}{\ln(P_{l_j, l_{j+1}})} \right) \quad (16)$$

Further, the gradient of the entropy of the power distribution on a relay node is given as:

$$\frac{\partial H}{\partial c_l} = \frac{\sum_{j=1}^N c_j(k) - c_l(k)}{\left(\sum_{j=1}^N c_j(k)\right)^2} \log \left[\frac{\sum_{j=1}^N c_j(k)}{c_l(k)} \right] + \frac{c_l(k) - \sum_{j=1}^N c_j(k)}{\left(\sum_{j=1}^N c_j(k)\right)^2}, \quad (17)$$

While the gradient of the entropy of the power distribution on the other nodes of the path is given as:

$$\frac{\partial H}{\partial c_i} = \frac{-c_i(k)}{\left(\sum_{j=1}^N c_j(k)\right)^2} * \text{Log} \left[\frac{\sum_{j=1}^N c_j(k)}{c_i(k)} \right] + \frac{c_i(k)}{\left(\sum_{j=1}^N c_j(k)\right)^2}. \quad (18)$$

Thus, the change of the entropy is:

$$\Delta \mathcal{H} = \bar{V}^T * \Delta \bar{c}(k).$$

The optimal path is the one that keeps this gradient minimum, thus enforcing only small changes in the energy entropy, guaranteeing that the energy distribution falls as close to its maximum as possible. In this way, a more or less uniform residual energy distribution can be maintained while sending packets to the BS. The optimum choice of relay nodes (i.e., the optimal path) which minimizes the change in the gradient can thus be obtained as:

$$l_{opt} = \min(\Delta H = \bar{V}^T * \Delta \bar{c}(k)). \quad (19)$$

After each round, the BS updates the residual energy vector of all nodes, $c(k) = (c_1(k), \dots, c_i(k), \dots, c_N(k))$, finds the optimal path from node i to the BS, and calculates the relay nodes of the path using OREBP. The BS broadcasts a new look-up-table containing the optimal routes of each node. This can help reduce the computational load on the nodes and improve their energy efficiency.

We will refer to this method of routing the packets to the BS as the Optimal Remaining Energy-Based Protocol (OREBP). The needed calculations increase as the number of maximum hops (m) increases; as the maximum number of hops (m) increases, more possible paths are available and more optimality is achieved.

6. Simulation Results

The performance of the proposed algorithms MMREP and OREBP, respectively are evaluated in comparison to the PEGASIS protocol. In PEGASIS, each node forwards the packet to its closest neighbor; when the packet arrives at the chain leader, it sends the packet directly to the base station.

PEGASIS does not take reliability into consideration, whereas MMREP and OREBP do. To introduce reliability constraints to PEGASIS and thus make it comparable with the proposed protocols, it is modified as follows: each packet should be forwarded to the BS with at least success probability $P_{ij} = (1 - \epsilon)$, where i is the source node and j is the destination node. From Equation (1) $P_{ij} = \exp(-d_{ij}^\alpha \frac{\theta \sigma_z^2}{g_{ij}})$, g_{ij} is calculated as in [26]. In case of an m -hop path, $P(\text{path}) = \sqrt[m]{1 - \epsilon}$. For the whole round, we will calculate the average success probability of all paths.

Figure 1 shows how 100 nodes are deployed randomly onto a grid of 100 m \times 100 m according to a 2D normal distribution; the BS is allocated in the upper-right corner of the sensing field, as shown by the green point. while Figure 2 shows the network as a graph. The highlighted chain is constructed by the Dijkstra shortest path algorithm, as defined by the base station.

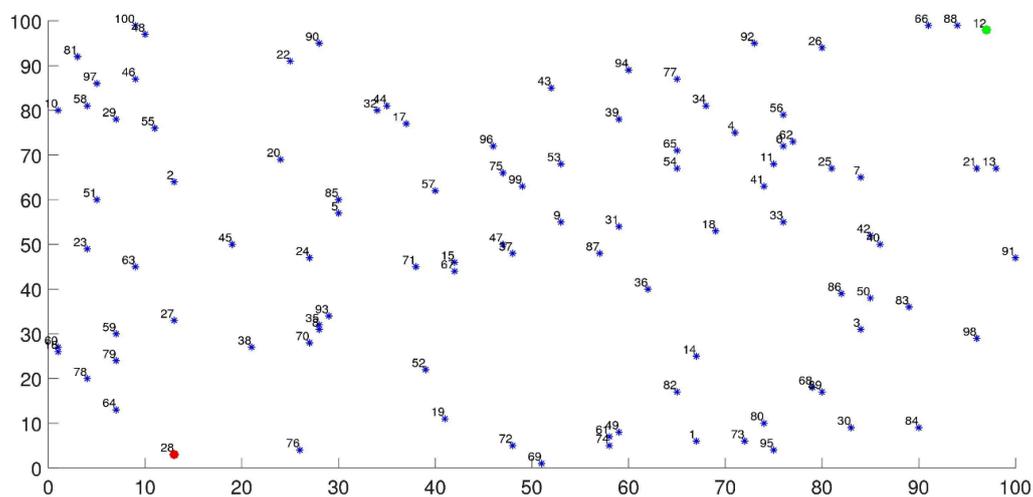


Figure 1. Simulated network.

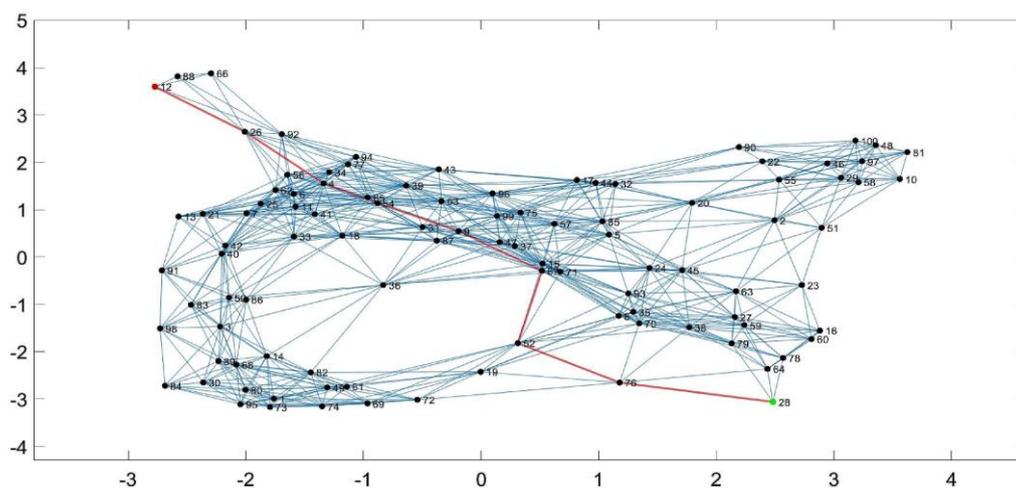


Figure 2. The network as a graph.

The transmission energy will be calculated according to the Rayleigh fading model (1) under the following assumptions:

- We neglect the conditioning energy needed by the electronics.
- $\theta = 10^{-6}$
- $\sigma_Z^2 = 0.1$
- $\alpha = 2$
- P_{ij} is calculated based on reliability $(1 - \varepsilon)$ and the number of relay nodes m , where $\prod_{j=0}^m P_{l_j, l_{j+1}} \geq 1 - \varepsilon$. We assume that P_{ij} is the same for all nodes, then $P_{ij} = \sqrt[m]{1 - \varepsilon}$.
- All the nodes have the same initial energy.
- The life span is the number of packets transmitted over the chain until the first node goes flat. Each transmission round carries a single packet.
- Each node has an adjustable power transmission, which enables it to access any node in the chain including the BS.

The path shown in Figure 2 consists of seven nodes, numbered from 1 to 7, where node number 1 is the farthest from the BS, it shown as red point in Figure 1. Figure 3 shows the residual energy of the nodes of the chain for MMREP, OREBP, and PEGASIS respectively, when the first node goes flat. In the case of MMREP and OREBP, we note that almost all the nodes have the same level of residual energy, the residual energy is distributed more uniformly (near zero) for all nodes, In the case of PEGASIS, we note that as the node gets further away from the BS, it loses energy at a higher rate, the residual energy of the nodes decreases as the nodes gets farther from the BS. So, we note unevenly distribution of the residual energy.

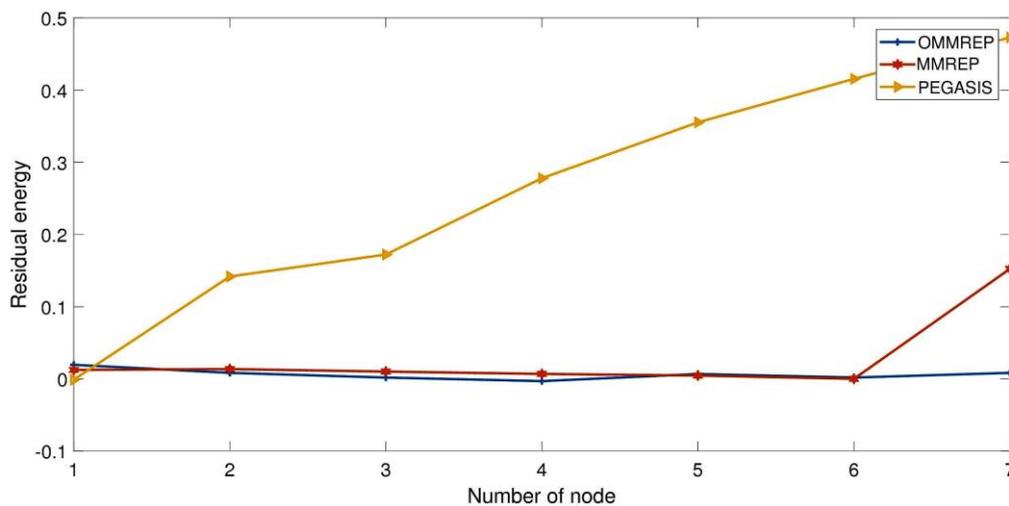


Figure 3. Distribution of residual energy on the path at the moment when the first node goes flat.

Figure 4 shows the life span of a network which uses MMREP, OREBP, PEGASIS, subject to a reliability constraint, with different data loss percentage ε values, 0.025, 0.05, 0.075, 0.01, 0.125 and 0.15, respectively. Since PEGASIS does not consider ε when calculating transmission energy, the figure shows that it has a higher life span than MMREP and OREBP; it uses lower transmission energy, which causes a higher packet loss percentage, which means lower reliability; hence, the life span of a network with PEGASIS is the same regardless of data loss percentage ε . In the case of the proposed algorithms, however, life span increases with increasing data loss percentage ε , while the probability of successful packet transmission $(1 - \varepsilon)$ is decreasing. With MMREP and OREBP, the life span is a function of ε . The users can trade-off between the reliability represented by ε and the life span.

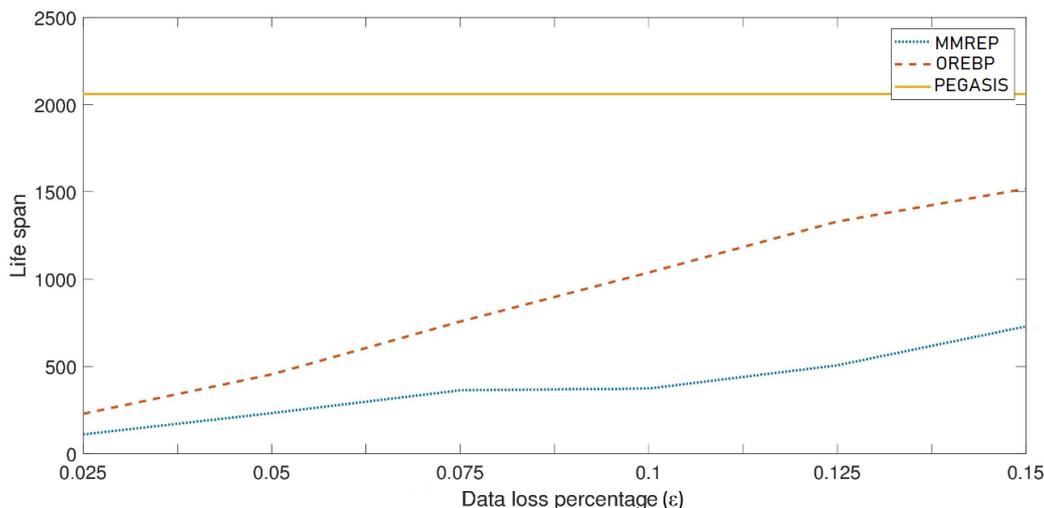


Figure 4. Life span with different data loss (ε).

Figure 5 shows the success probability with OREBP and PEGASIS. We assume a predefined data loss rate (ε = 0.05) for OREBP. The success probability for PEGASIS is calculated as mentioned above. The figure shows the success probability against a variable number of hops ranging from one to six. OREBP always has a higher success probability than PEGASIS, although the value depends on the number of hops. The figure shows that using OREBP improves the reliability from 63% in case of a one-hop path to 71% in case of a six-hop path. Lost data means wasted energy. The figure shows that the success probability decreases with an increasing number of hops. In OREBP, we can control the success probability by trading off between predefined data loss (ε) with life span, as shown in Figure 4.

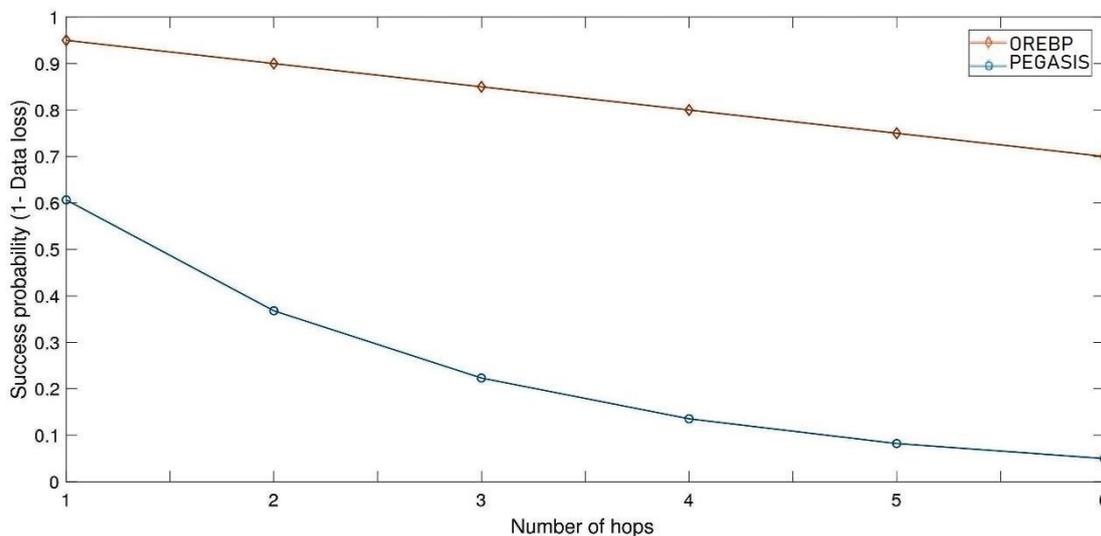


Figure 5. Success probability when data loss (ε = 0.05).

Figure 6 shows the relationship between the life span and the number of hops with MMREP, OREBP, and PEGASIS. We assume a predefined data loss rate (ε = 0.05). In the case of MMREP, OREBP, the consumed energy depends on ε. The probability of the overall success of packet transmission from the source node to the BS should satisfy $\prod_{j=0}^m P_{l_j l_{j+1}} = 1 - \epsilon$, where m is the number of the hops. The figure shows the life span against a variable number of hops ranging from one to four. We note that the life span with OREBP increases as the number of hops increases. But, in the case of MMREP, the relationship is unstable because the set of Equations (11) is solved numerically, where a set of

solutions are found, so, one needs an algorithm to pick the suitable solution. In OREBP, life span increases as the number of maximum hops increases because there are more paths available to select from. With PEGASIS, the consumed energy is a function of single transmissions rather than the path overall transmissions, so it does not depend on the number of hops.

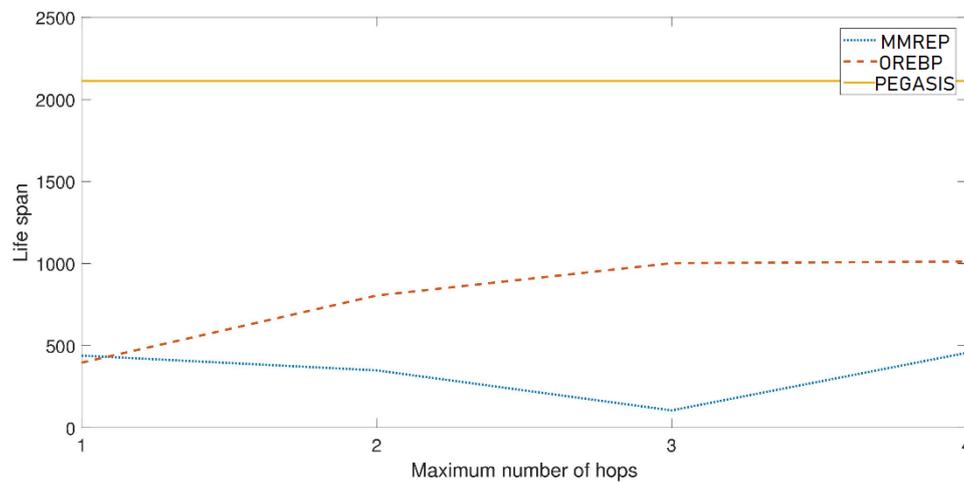


Figure 6. Life span and maximum number of hops ($\epsilon = 0.05$).

As the number of hops increases, not only the life span increases, but also the complexity of the algorithm increases. Figure 7 shows the relationship among the maximum number of hops m , on the x -axis, the life span y -axis on the left, and the execution time (a proxy for the complexity) on the secondary y -axis on the right. As expected, the figure shows that in OREBP as the number of hops increases, the life span increases, but the complexity of the protocol also increases. The user has the choice of trade-offs between the life span, the complexity, and the maximum number of hops.

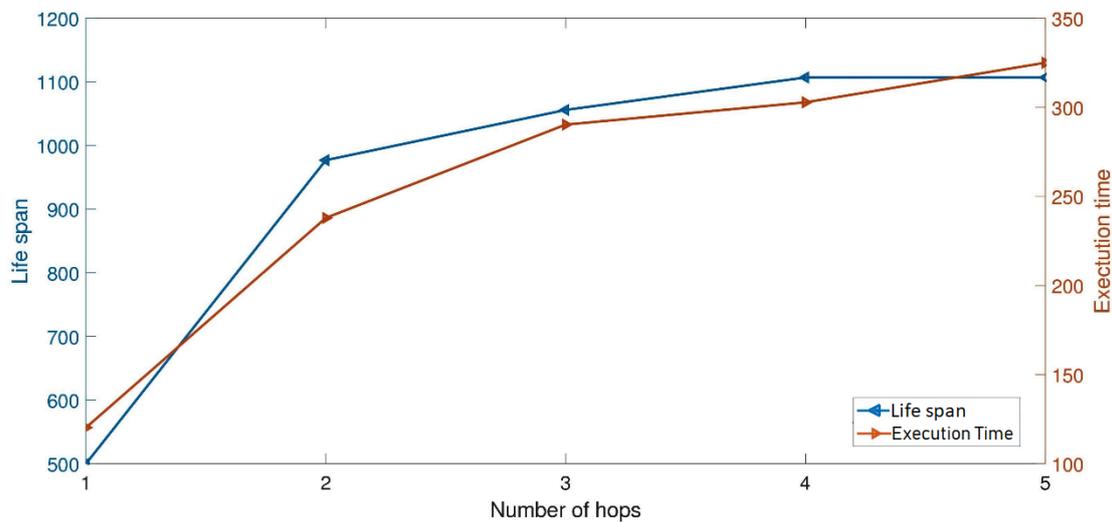


Figure 7. Life span, number of hops, and execution time.

All the figures show higher a life span with PEGASIS, but also a high percentage of lost data, which implies wasted energy. The results show that the performance of OREBP is better than the performance of MMREP. As we mentioned, MMREP is the basic idea of the algorithm, but we used the entropy principle to optimize it and to reduce its complexity.

7. Conclusions

In this paper, we introduced a protocol which maximizes the minimum residual energy subject to a predefined reliability constraint. We optimized the energy balancing of WSNs by a new protocol (OREBP) to achieve uniform energy consumption by maximizing an entropy-like measure. As demonstrated by the simulation results, the proposed protocols improve the energy efficiency of WSNs by maximizing the life span, subject to a reliability constraint. They also improve the energy consumption distribution among the nodes of the network. The performance of the proposed protocols is compared to the performance of PEGASIS. As shown, the proposed protocols still have a high degree of complexity. We defined four performance parameters: life span, data loss percentage, the maximum number of hops, and the complexity. The user has the choice to control the performance by striking an optimal trade-off among these parameters. To achieve this requires a solution of a complicated optimization problem.

Author Contributions: Conceptualization, M.A. and J.L.; Methodology, M.A. and J.L.; Software, M.A.; Validation, M.A. and J.L.; Formal Analysis, J.L.; Investigation, M.A.; Resources, M.A.; Data Curation, M.A.; Writing-Original Draft Preparation, M.A.; Writing-Review & Editing, J.L.; Visualization, M.A.; Supervision, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The research reported in this paper was supported by the Higher Education Excellence Program of the Ministry of Human Capacities in the frame of Artificial Intelligence research area of Budapest University of Technology and Economics (BME FIKP-MI/SC).

Conflicts of Interest: We declare that no conflict of interest.

References

1. Akyildiz, I.F.; Mehmet, C.V. *Wireless Sensor Networks*, 1st ed.; John Wiley & Sons: Hoboken, NJ, USA, 2010.
2. Cao, N.; Zhao, Y.; Liang, J.; Wang, T.; Huang, T.; Xu, D.; Xu, Y. The Comparison of Single-Hop and LEACH Protocols in Wireless Sensor Networks. In Proceedings of the 2017 IEEE International Conference on Computational Science and Engineering (CSE) and IEEE International Conference on Embedded and Ubiquitous Computing (EUC), Guangzhou, China, 21–24 July 2017; Volume 2.
3. Kafi, M.A.; Othman, J.B.; Badache, N. A survey on reliability protocols in wireless sensor networks. *ACM Comput. Surv.* **2017**, *50*, 31. [[CrossRef](#)]
4. Tifenn, R.; Bouabdallah, A.; Challal, Y. Energy efficiency in wireless sensor networks: A top-down survey. *Comput. Netw.* **2014**, *67*, 104–122.
5. Ahmed, K.J.; Qureshi, H.K.; Iqbal, A. Energy management in wireless sensor networks: A survey. *Comput. Electr. Eng.* **2015**, *41*, 159–176.
6. Zahariadis, T.; Trakadas, P. Design Guidelines for Routing Metrics Composition in LLN, Internet-Draft Submitted to IETF Networking Working Group, ROLL Subgroup, 23 November 2012. Available online: <https://tools.ietf.org/html/draft-zahariadis-roll-metrics-composition-04> (accessed on 1 January 2020).
7. Mohamed, R.E.; Ghanem, W.R.; Khalil, A.T.; Elhoseny, M.; Sajjad, M.; Mohamed, M.A. Energy efficient collaborative proactive routing protocol for wireless sensor network. *Comput. Netw.* **2018**, *142*, 154–167. [[CrossRef](#)]
8. Treplan, G.; Long, T.; Janos, L. Energy efficient reliable cooperative multipath routing in wireless sensor networks. *World Acad. Sci. Eng. Technol.* **2010**, *68*, 1366–1371.
9. Heinzelman, W.; Chandrakasan, A.; Balakrishnan, H. Energy-Efficient Communication Protocols for Wireless Microsensor Networks. In Proceedings of the 33rd Annual Hawaii International Conference on System Sciences, Maui, HI, USA, 4–7 January 2000.
10. Pantazis, N.A.; Stefanos, A.N.; Dimitrios, D.V. Energy-efficient routing protocols in wireless sensor networks: A survey. *IEEE Commun. Surv. Tutor.* **2013**, *15*, 551–591. [[CrossRef](#)]
11. Shweta, V.; Kuma, R. Variants of LEACH routing protocol in WSN: A comparative analysis. In Proceedings of the 2018 8th International Conference on Cloud Computing, Data Science & Engineering (Confluence), Noida, India, 11–12 January 2018.

12. Ke, W.; Yangrui, O.; Hong, J.; Heli, Z.; Xi, L. Energy aware hierarchical cluster-based routing protocol for WSNs. *J. China Univ. Posts Telecommun.* **2016**, *23*, 46–52. [[CrossRef](#)]
13. Ni, Q.; Pan, Q.; Du, H.; Cao, C.; Zhai, Y. A novel cluster head selection algorithm based on fuzzy clustering and particle swarm optimization. *IEEE/ACM Trans. Comput. Biol. Bioinforma.* **2015**, *14*, 76–84. [[CrossRef](#)] [[PubMed](#)]
14. Amit, S.; Murugan, T.S. Cluster head selection for energy efficient and delay-less routing in wireless sensor network. *Wirel. Netw.* **2019**, *25*, 303–320.
15. Yu, B.; Choi, W.; Lee, T.; Kim, H. Clustering Algorithm Considering Sensor Node Distribution in Wireless Sensor Networks. *J. Inf. Process. Syst.* **2018**, *14*, 926–940.
16. Lakshmanarao, B.; Vamsikrishna Raja, P. Power Efficient Gathering in Sensor Information Systems Protocol Using K-means Clustering Algorithm. *Int. J. Sci. Eng. Comp. Technol.* **2016**, *6*, 133.
17. Chen, K.; Jyh-Ming, H.; Chieh-Chuan, H. CHIRON: An energy-efficient chain-based hierarchical routing protocol in wireless sensor networks. In Proceedings of the 2009 Wireless Telecommunications Symposium, WTS 2009, Prague, Czech Republic, 22–24 April 2009.
18. Yu, Y.; Song, Y. An energy-efficient chain-based routing protocol in wireless sensor network. In Proceedings of the 2010 International Conference on Computer Application and System Modelling (ICCSM 2010), Taiyuan, China, 22–24 October 2010; Volume 11.
19. Mishra, A.K.; Rahman, R.U.; Bharadwaj, R.; Sharma, R. An Enhancement of PEGASIS Protocol with Improved Network Lifetime for Wireless Sensor Networks. In Proceedings of the Power, Communication and Information Technology Conference (PCITC), Bhubaneswar, India, 15–17 October 2015; pp. 142–147.
20. Natasha, R.; Bassoo, V. Energy-efficient chain-cluster based intelligent routing technique for Wireless Sensor Networks. *Appl. Comput. Inform.* **2018**. [[CrossRef](#)]
21. Taghikhaki, Z.; Meratnia, N.; Havinga, P. A reliable and energy-efficient chain-cluster based routing protocol for Wireless Sensor Networks. In Proceedings of the 2013 IEEE Eighth International Conference on Intelligent Sensors, Sensor Networks and Information Processing, Melbourne, Australia, 2–5 April 2013.
22. Liaqat, T.; Akbar, M.; Javaid, N.; Qasim, U.; Khan, Z.A.; Javaid, Q.; Alghamdi, T.A.; Niaz, I.A. On Reliable and Efficient Data Gathering Based Routing in Underwater Wireless Sensor Networks. *Sensors* **2016**, *16*, 1391. [[CrossRef](#)] [[PubMed](#)]
23. Ai, Z.-Y.; Zhou, Y.-T.; Song, F. A smart collaborative routing protocol for reliable data diffusion in IoT scenarios. *Sensors* **2018**, *18*, 1926. [[CrossRef](#)] [[PubMed](#)]
24. Keller, L.; Atsan, E.; Argyraki, K.; Fragouli, C. SenseCode: Network coding for reliable sensor networks. *ACM Trans. Sens. Netw.* **2013**, *9*, 25. [[CrossRef](#)]
25. Rout, R.R.; Ghosh, S.K. Adaptive data aggregation and energy efficiency using network coding in a clustered wireless sensor network: An analytical approach. *Comput. Commun.* **2014**, *40*, 65–75. [[CrossRef](#)]
26. Levendovszky, J.; Bojársky, A.; Karlocai, B.; Olah, A. Energy balancing by combinatorial optimization for wireless sensor networks. *WSEAS Trans. Commun.* **2008**, *7*, 27–32.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).