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Joint Balanced Routing and Energy Harvesting Strategy for Maximizing Network Lifetime in WSNs

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Abstract: Nowadays, wireless sensor networks (WSNs) are becoming increasingly popular due to the wide variety of applications. The network can be utilized to collect and transmit numerous types of messages to a data sink in a many-to-one fashion. The WSNs usually contain sensors with low communication ability and limited battery power, and the battery replacement is difficult in WSNs for large amount embedded nodes, which indicates a balanced routing strategy is essential to be developed for an extensive operation lifecycle. To realize the goal, the research challenges require not only to minimize the energy consumption in each node but also to balance the whole WSNs traffic load. In this article, a Shortest Path Tree with Energy Balance Routing strategy (SPT-EBR) based on a forward awareness factor is proposed. In SPT-EBR, Two methods are presented including the power consumption and the energy harvesting schemes to select the forwarding node according to the awareness factors of link weight. First, the packet forwarding rate factor is considered in the power consumption scheme to update the link weight for the sensors with higher power consumption and mitigate the traffic load of hotspot nodes to achieve the energy balance network. With the assistance of the power consumption scheme, hotspot nodes can be transferred from the irregular location to the same intra-layer from the sink. Based on this feature, the energy harvesting scheme combines both the packet forwarding rate and the power charging rate factors together to update the link weight with a new battery charging rate factor for hotspot nodes. Finally, simulation results validate that both power consumption and energy harvesting schemes in SPT-EBR achieve better energy balance performance and save more charging power than the conventional shortest path algorithm and thus improve the overall network lifecycle.

Keywords: Wireless Sensor Network; Dijkstra routing algorithm; load balance; power consumption; energy harvesting

1. Introduction

Wireless sensor networks (WSNs) have caused a lot of attention among scholars due to the growth of the Internet-of-Things (IoT) [1], and have achieved a wide success in daily life and industrial applications, such as smart grid [2], safety monitoring [3], and risk prevention [4]. The lifecycle of sensor nodes generally depends on the supplied battery power and numerous possible deployment methods to avoid unnecessary power depletion, including data processing, power control [5], energy efficient routing [6], etc. Long-term monitoring service is a key purpose for designing WSNs, but it is notably influenced by the network energy imbalance [7]. The challenge study issue of maximizing network lifecycle is preventing the energy imbalance, the condition happens when some nodes are exhausted, while others have plenty of residual energy, causing hotspot nodes in data transmission networks [8,9].

Directly sending packets with long distances from sensors to the data sink is unattractive, the routing protocols are usually designed in a multi-hop fashion, which can be classified into two cases: flat routing [10] and hierarchical routing [11]. In the flat routing case, routing paths from the sending sensors to sink are computed according to the minimum energy cost. The energy expense can be reduced by using shorter distance communication. In the hierarchical routing case, the network topology is constructed by clusters, and each cluster head (CH) is able to fuse packets with data correlations; hence, it is helpful for removing redundant packets, and decreases the total amount of packets, thus improves operation lifecycle.

Inventing a particular routing algorithm for energy efficient packet transmission is one main research direction. To consider the transmission costs and remaining battery power of sensors in [12], the authors formulate the network lifecycle maximum problem to a linear optimization problem and select the optimal shortest paths with the lowest cost, and near optimal lifecycle can be reached. To consider routing optimization in scenarios with obstacles in [13], a geographical routing is presented for the shortest path selection by using the Dijkstra algorithm. Each sensor is able to determine routing path according to location information of itself and the adjacent sensors, thus it is appropriate for the large scale WSNs. Another direction for balancing energy consumption is the modification on the typical flat and hierarchical routing schemes. To eliminate the unbalance power consumption of CH, the author in [14] studied how to determine the optimal cluster size for a decentralized hierarchical network. In addition, a General Self-Organized Tree-Based Energy-Balance (GSTEB) routing protocol is proposed in [15] to dynamically update the tree routing topology for the real-time situation and nodes can cooperate with each other via beacons to select the next node by their own routing decisions. Although all CHs produce an equal number of collected packets in [16], which leads the energy imbalance problem around the sink connection area (SCA), while causing underutilized energy for all the other sensors. Consequently, the research challenge issues in developing energy balance routing protocol are to equalize the power consumption among hotspots and achieve better power utilization of other sensors to improve the overall network lifecycle [17–19].

Another favorable technology to improve the lifecycle of WSNs is contributed by the recent energy harvesting models [20–23]. Each sensor captures the energy from the surrounding environment with energy harvesting abilities, including solar radiations or vibrations, and collects the energy into its own rechargeable battery. Therefore, it has a high probability to achieve the immortal WSNs when the energy harvest amount in each node is greater than the energy consumption amount for packet transmission. However, the major limitation of the method is the intermittent energy capture, which can make the network performance degraded.

To mitigate the irregular energy harvesting problem, wireless power transfer (WPT) transmits power distantly to the sensors, which provides an attractive opportunity for harvesting ambient energy [22]. Given the wireless charger, the energy transfer to the sensors can be controlled and make the network optimization in lifecycle extension. In [23], the authors optimize the network lifecycle performance under the condition that the energy consumption by each sensor is less than its harvested energy. Hence, the network operation lifecycle depends on not only how the wireless charger transfers the power to the sensors, but also how the sensors spend the reception power.

To jointly consider the energy balanced routing and energy harvesting benefits, a Shortest Path Tree with Energy Balance Routing strategy (SPT-EBR) is proposed in this article. In SPT-EBR, two methods are presented including the power consumption and the energy harvesting schemes to select the forwarding node according to the awareness factors of link weight. The SPT-EBR is a positive and early-intervention method, and includes the following contributions:

(1) To avoid excessive load concentration among SCA, a power consumption scheme is presented to generate the multiple shortest path trees in the early stage for data dissemination and distributes traffic load to the path trees according to the packet forwarding rate factor. The contribution is to

improve the construction of routing solution and avoid the frequent routing update messages causing the excessive load concentration, thus prolonging the network lifecycle.

(2) In addition, the power consumption scheme is utilized to transfer some traffic load in the congested SCA to several sub-trees with the lowest load. This makes a part of paths with good load-balance level and high energy efficiency during the iteration process of the algorithm. As a result, each intra-layer from the sink can be expected to have the similar traffic load in terms of the balanced power consumption. The intra-layer is defined as the nodes with the same hop length to the sink.

(3) Using the late-remedy routing solutions [15,16], hotspot nodes are usually spatially distributed. With the assistance of the power consumption scheme, hotspot nodes can be transferred from the irregular location to the same intra-layer and this benefit makes the implementation of efficient wireless power charging over a large area is possible.

(4) To achieve the design aim of immortal WSNs, an energy harvesting scheme is proposed to jointly combine both the packet forwarding rate and the power charging rate factors together to make the energy charging efficient for the hotspots in the SCA. With the assistance of load balancing on SCA and energy harvesting, the contribution helps to accelerate the generation of the whole network balance routing solution, improving both the routing survivability and energy harvesting efficiency, as well as prolonging the network longevity.

The remainder of this paper is arranged as follows. The literature review is introduced in Section 2. Section 3 presents the problem statement and motivation. In Section 4, a network model is introduced and the SPT-EBR is presented including the power consumption and the energy harvesting schemes. In Section 5, the power consumption performances between the SPT-EBR and the Dijkstra algorithms are compared and the benefits of energy harvesting scheme are also demonstrated with computer simulations. Finally, conclusions are described in Section 6.

2. Related Work

2.1. Routing Based on Forwarding Factors

Many types of load-balanced transmission strategies have been proposed, including routing based on forwarding factors, hybrid power transmission, power control, etc. In the routing based on forwarding factors [16,24–27], routing paths are usually selected in accordance with several forwarding factors, such as the residual battery capacity, the distance to the sink, the degree of the nodes, and so forth.

The authors in [24] studied the ant colony optimization(ACO)-based path selection schemes by considering several factors, including the battery level of forwarding nodes, the distance to the sink, the travelled distance, and so on. Based on the one-dimensional queue network, the authors in [25] proposed an opportunistic routing protocol by considering forwarding factors with the distance to the sink and the remaining battery capacity of the sensors. Based on the multiple forwarding factors, a position-aware routing scheme [26] is proposed to consider the factors of the residual energy, node degree, and distance to the sink to balance the node energy and improve the network lifetime. A mixed transmission scheme is proposed in [27] that each node trades off between the multi-hop and single-hop transmission to extend the network lifetime by considering the forwarding factors including the link reliability, the degree of nodes and the remaining battery capacity. In [16], two hybrid multi-hop/single-hop transmission strategies (power efficiency and power utilization strategies) with adaptive routing are proposed to extend the network lifetime of wireless sensor networks (WSNs). The power efficiency strategy aims to minimize the overall power consumption and the power utilization strategy endeavors to minimize the maximum power consumption among hotspots. In addition, the adaptive routing method is a late-remedy method to consider the channel status in each operation round.

2.2. Wireless Power Transfer

With recent energy harvesting models, optimizing data routing is a common approach to reduce energy consumptions of the nodes and improve the lifecycle of WSNs. Considering the power transfer task, the chargers construct power beams [28] to improve the wireless power transfer (WPT) efficiency, such that more power could be harvested by the sensors. To maximize the power reception by the sensor, the present approaches are based on the dominant channel eigenvector of energy beam [29,30]. Even the energy beamforming is optimized; if the nodes consume energy inefficiently, the power would be wasted and the network lifecycle performance will be degraded. To maximize the network lifecycle and achieve the immortality of the WSNs, the authors propose to reduce the energy consumption of sensors by optimizing the data routing among the sensors and to improve the WPT efficiency by optimizing the energy beamforming of the chargers [31].

Energy harvesting and WPT are capable of relieving the battery limitation of sensors, an amplify-and-forward relay network (AF-RN) is proposed in [32]. The strategy is a joint power control and energy transfer scheme to maximize the throughput by considering the energy causality constraints. In [33], an AF-RN with energy harvesting (EH) source and relay nodes is investigated. To consider the energy arrival profiles and the energy cooperation between EH nodes, a joint power control and transfer is designed to maximize the total data rate, subject to energy causality and battery storage constraints. With the total source transmission power budget and energy-causality constraints, the authors in [34] formulated an energy efficiency maximization (EEM) optimization problem for the multi-user multicarrier energy-constrained amplify-and-forward (AF) multi-relay network. Under the simultaneous wireless information and power transfer (SWIPT) model, each forwarding node is solely powered by the source nodes, employing an energy harvesting time-switching (EHTS) scheme to harvest the energy via the radio-frequency (RF) signal transmitted from the source nodes. In addition, a suboptimal and best relay selection algorithm is also examined to trade-off between complexity and performance.

The above energy balance approaches seem to be comprehensive; however, they are just passive and late-remedy solutions based on multiple forwarding factors to determine an appropriate routing path. On the other hand, the above efficient wireless charging schemes consider the efficient routing node selection instead of the balanced routing node determination. To jointly consider the design issues on the balanced routing and the effective WPT, a SPT-EBR is proposed to improve the load balance and thus improve the WPT efficiency. The SPT-EBR is an early-intervention method to make the load balancing in the SCA layer and all the other intra-layers. The proposed method can also avoid the frequent routing update messages and the excessive load concentration in the following maintenance phase. After load balance in each intra-layer, the energy harvesting scheme can be applied to efficiently charge for the hotspot nodes.

3. Problem Statement and Motivation

3.1. Problem Statement

When considering traditional multi-hop routing with many-to-one traffic patterns, unbalanced energy consumption is an inherent problem in WSNs. However, the multi-hop routing method can achieve better energy efficiency than the single-hop routing method in networks. In the multi-hop routing method, each sensor node can transmit and forward packets to the data sink through the shortest path, either occasionally or periodically. After a period of operation, hotspot nodes will be generated when the high traffic routing paths are converged and most of the traffic load congested at some specific nodes. Typically, sensors near the sink forward a larger amount of traffic load than sensors that are far from the sink. Therefore, the hotspot nodes near the data sink deplete the battery faster than other sensors. Since the network operation lifecycle is usually defined as the occasion when a battery of the first node is exhausted, the remaining energy capacity of other sensors can be regarded as underutilized energy, and the energy consumption discrepancy results in the considerable network lifetime degradation.

A traditional hierarchical WSN routing scenario that includes 81 clusters with one data sink and an evenly distributed two-dimensional network is shown in Figure 1. According to the energy capacity, a cluster head (CH) is selected from the sensors in each cluster. In the cluster, each CH is responsible to manage the sensors, merges all the sensing data from sensors, and sends the collected data to the sink. In order to achieve balance energy utilization, the node with the largest remaining battery capacity is designated as a CH in turn.

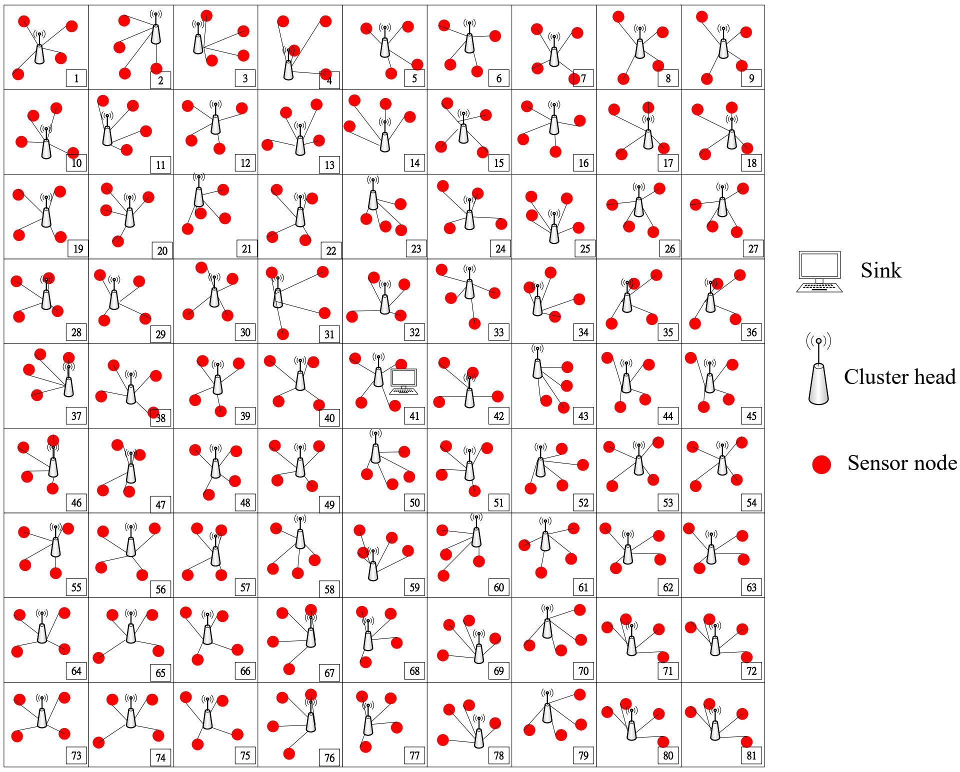

Figure 1. An 81-cluster example illustration for wireless sensor networks (WSN) deployment.

In the WSNs example, it is assumed that the nodes are deployed in a uniform distribution; the communication distance between two adjacent nodes is d. Each node transmits the sensing data to the sink through the forwarding node along the shortest path. The power consumption is assumed to be proportional to d^2 in the path loss model. Note that the shortest path from each node to the sink is calculated by the Dijkstra algorithm. From the perspective of data application, the traffic generated in each node is periodically sent to the target sink. After a specific network operation cycle, each node calculates the number of sending and forwarding packets, and then sends the statistics of the total transmitted packets along with data packets to the sink. Finally, the statistics of each node are calculated by the sink to estimate the number of paths forwarded.

In Figure 2, the average forwarding path load amount is illustrated. The 36 nodes in the red area are mainly forwarded through the node 32, the 20 nodes in the blue area are mainly forwarded by the node 40, the 20 nodes in the green area are mainly forwarded via the node 42, and the four nodes in the purple area are mainly forwarded by the node 50. Even though both nodes 32 and 50 are directly connected to the sink, the number of packets forwarding via node 32 is nine times that of node 50. Therefore, an interesting phenomenon is observed which leads to uneven traffic load among the sink in the network even with a uniform node distribution and each node has a uniform packet transmission rate. Specifically, the power consumption rate is unbalanced in the sink connectivity area (SCA), where the power consumption rate can be calculated by the total number of packets sent and forwarded in the period of each node.

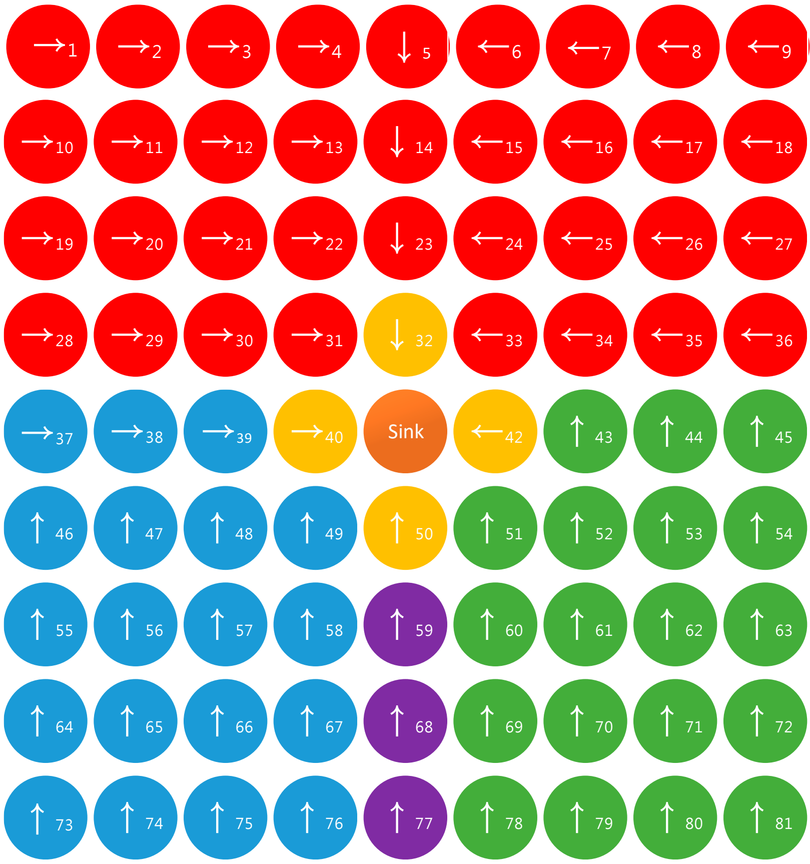

Figure 2. An illustrated example of packet forwarding amount for the sink connection area (SCA).

In the SCA, it is expected that the four primary forwarding nodes 32, 40, 42, and 50 achieve the approximate power consumption rate per operation cycle. Unfortunately, the Dijkstra algorithm uses the first shortest path and does not consider the following shortest paths; a non-uniform forwarding packet load distribution phenomenon was found in the SCA. In addition, the battery capacity of node 32 was first exhausted because the number of packets forwarded by the primary forwarding node adjacent to the data sink presents an uneven load distribution. The earliest exhausted node also causes the sub-area network to be unserved, thereby reducing the lifetime of the entire network. As a result, there are 35 nodes with good battery conditions, but these nodes cannot send data packets to the data sink through the primary forwarding node 32. As a result, the energy resource of the other nodes is not fully utilized in terms of the overall network underutilization. To improve the routing survivability, the highest traffic load can be transferred to several sub-trees with the least load, in order to speed up load balance among different nodes of the network.

3.2. Motivation

With the same link weight in each path, the Dijkstra algorithm computes the shortest path for all nodes of multi-hop network initially. After that, the routing path of each node changes as the path cost variation. To mitigate the power consumption of the hotspot nodes, the nodes with lighter traffic can share the forwarding packets if the hotspot nodes increase their path costs. At the same time, because the packet forwarding amount of hotspots next to the sink is very large, the packet forwarding rate is much higher than other nodes. Therefore, it is possible to design an energy balanced routing strategy by the amount of packet forwarding in each node and the packet forwarding rate can be utilized as a forward awareness factor of path cost or link weight. It can be expected that after several transmission cycles, the SCA and other nodes in each communication layer centered at the sink can achieve the effect of load balance in terms of the energy balance of each network layer.

In Figure 2, four main forwarding nodes directly connected to the sink can be observed that the number of forwarding packets via node 32 is nine times than that of node 50. We aimed to design a method with the packet forwarding rate for the path cost and to achieve the effect of load balancing of the four main forwarding nodes. Taking node 9 as an example in Figure 1, node 9 can reach sink 41 either from the primary node 32 or 42. Originally, the resulting shortest path is 9→8→7→6→5→14→23→32 by the Dijkstra algorithm. After a certain period of operation, if the forwarding amount of node 32 is greater than the other primary nodes in SCA, the path cost of node 32 is increased and an alternative path 9→8→7→15→25→34→33→42 could be generated. Thus, the packets originally forwarded by the node 32 will be forwarded by the node 42 afterward and the traffic load of node 32 can be mitigated. After that, when the forwarding amount of the node 42 is relatively increased and the path cost of the node 42 will be increased. As a result, the shortest path for node 9 can be alternative switched either via node 32 or node 42.

On the other hand, the forwarding traffic load via node 42 such as nodes 78 to 81 will also be transferred to node 50, since it has a small number of forwarding packets than node 42. After changing the path cost of hotspots to update the new routing paths of other sensors, our first aim is to design a uniform forwarding packet rate for the main forwarding nodes and all the other communication layers. In addition, the hotspot nodes location can be transferred from the irregular distributed area into the SCA intra-layer. Finally, the ideal balanced shortest tree of multi-hop networks can be seen in Figure 3. Based on the balanced shortest tree routing, the energy harvest capability is jointly deployed for each sensor to effectively utilize the harvested energy and towards to achieve the main goal for an immortal WSN.

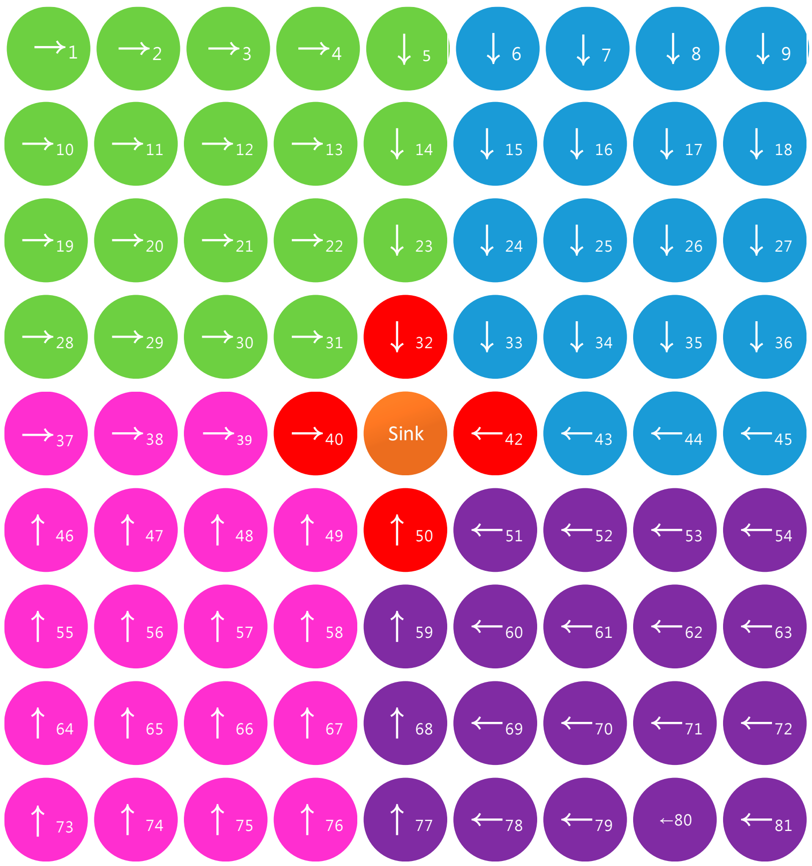

Figure 3. The ideal balanced shortest tree of multi-hop networks.

4. The Proposed Strategy

4.1. The Network Model

It is assumed that all sensors are evenly distributed in a two-dimensional region R with a radius of d for the network model. With unlimited energy, a static data sink is located at the center of the two-dimensional region. Each sensor is located within a cluster and transmits the sensed packet to its associated cluster head (CH). Then each CH aggregates and transmits packets along with the constructed shortest paths to the data sink. To evenly assign the CH among sensors, the CH is alternated with an equal probability in the same cluster and all sensors have the same amount of initial energy E_{init} [9].

In the network application, each sensor collects parameters such as humidity, temperature, air quality, or other related events at the outside environment and the fused data can be forwarded to the sink via the CHs along the transmission path. Where m is a variable that is represented the total amount of sending packets and forwarding packets from CH u to the sink. In each data cycle, p_k is the probability that a CH fuses the kth event and generates number of packets g_k. As a result, the packet generation rate r for any CH u in each data cycle can be expressed as:

$$r_u = \sum_{k=1}^{m} p_k g_k \tag{1}$$

To simplify the power computation model, the transmission power is the main factor to be taken into consideration in the path loss model since it spends a larger amount of power than the reception and idle situations. Hence, the power consumption for the multi-hop transmission can be represented as $P_M(r_u)$. Consequently, the network lifecycle of CH node u is expressed by:

$$N(u) = \frac{E_{init}}{P_M(r_u)} \tag{2}$$

where E_{init} is the initial amount of battery capacity of each sensor and the lifecycle is defined as the network operation round from sensors placement till the first sensor depletes its battery capacity [16].

4.2. The Proposed SPT-EBR Strategy

In order to prolong the lifecycle of WSNs with node energy efficiency and energy balance, this paper proposes two novel schemes by using forward awareness factors as path cost to select the next node for packet transmission. One is the power consumption scheme, and the other is the energy harvesting scheme. The power consumption scheme considers the packet forwarding rate as the forward awareness factor for each node to alter the desired routing path. The packet forwarding rate is proportional to the power consumption rate and it is considered to keep the sensors using the shortest path, thus making the packets transmission efficient. Simultaneously, the power consumption between the hotspots is also balanced, achieving the effect of both packet transmission efficiency and load balancing design goal.

In general, hotspot nodes are usually spatially distributed. With the assistance of the power consumption scheme, hotspot nodes can be transferred from the irregular location to the same intra-layer, and this benefit makes the implementation of efficient wireless power charging over a large area is possible. In the energy harvesting scheme, it is assumed that the network nodes have the capability to capture energy. The role of the charging station can be deployed by a nearby data sink or other RF base stations, and the sensing node can be charged in a random model or a constant model. The power charging rate in each node is combined with the packet forwarding rate as the forward awareness factor to calculate the path cost for next node selection, achieving the design goal of energy balance and permanent utilization WSNs.

4.2.1. The Power Consumption Scheme

In the power consumption rate scheme, time resource is allocated as a time slot that operates periodically to avoid frequent paths updating. In the beginning, the sink calculates the shortest path from all nodes to itself by the Dijkstra algorithm. The shortest path is then passed from sink to each sensor to establish a minimum spanning tree routing. Packets transmission with the shortest path will make the transmission of the entire network more energy efficient. In each time slot, each node calculates whether its own packet transmission rate is greater than the threshold value. The threshold value is determined by the sink and can be defined as the average of the overall packet forwarding rate. Then, the sink passes the threshold value to all nodes together when the routing paths are transmitted. After that, each node can update the path cost according to the threshold value.

In each time slot, if the total amount of packet transmission value P is greater than the threshold T in each node, the path cost is increased by one. When the packet transmission amount P of the node is less than or equal to T, the value of path cost keep the same. In order to avoid communication overhead, path cost can be transmitted to the sink along with the sensing data. When the sink receives the data, if the path cost changes, the sink recalculates and updates the path to the nodes with high traffic load.

In each time slot, the node with a faster packet transmission rate can mitigate forwarding packets by increases the path cost. Let other nodes near the sink share the network traffic load and achieve the traffic load balance in each layer of the network. Repeat the load balancing operation can balance the transmission packets of the hotspot nodes since the hotspots can share the forwarding packets in turn from all the other sensors. Distributing the traffic load allows network load balancing to be achieved while letting the global nodes to fully utilize their energy. Alternatively, the shortest path transmission also minimizes overall power consumption for efficient energy utilization. Generally, the power consumption scheme achieves both energy efficiency and energy balance to extend the overall network lifecycle. The detail design flowchart of the power consumption scheme is shown in Figure 4.

4.2.2. The Energy Harvesting Scheme

Wireless renewable sensor network is another major research issue in this paper. Assuming that the nodes have energy capture capabilities, the sensing nodes can replenish energy from the energy radiated by the solar or RF base stations. Here, an integration of power charging rate and data forwarding rate is proposed as shown in Figure 5. The operation calculation cycle is scheduled from $t(0)$, $t(1)$, $t(2)$ to $t(n)$ time slots. At each operation cycle, each node has the opportunity to capture random ambient energy $a(i)$, which represents the power capture rate of the i-th node. The packet transmission rate can be converted into the function of the power consumption rate in each node, and the packet transmission rate is proportional to the power consumption rate. Therefore, the packet transfer amount P is converted into a corresponding power consumption function $p(i)$, which represents the power consumption of the i-th node at each time slot. The initial battery capacity of each node is $b(0)$, and the new battery capacity is updated in each time slot. The current battery capacity $b(i)$ can be obtained from the previous battery capacity $b(i-1)$, plus the current charging energy $a(i)$ and minus the power consumption rate for packets transmission. The current battery capacity can be formulated in Equation (3):

$$\begin{gathered} b(i) = b(i-1) + a(i) - p(i) \\ i = 1, 2, 3 \ldots n \end{gathered} \tag{3}$$

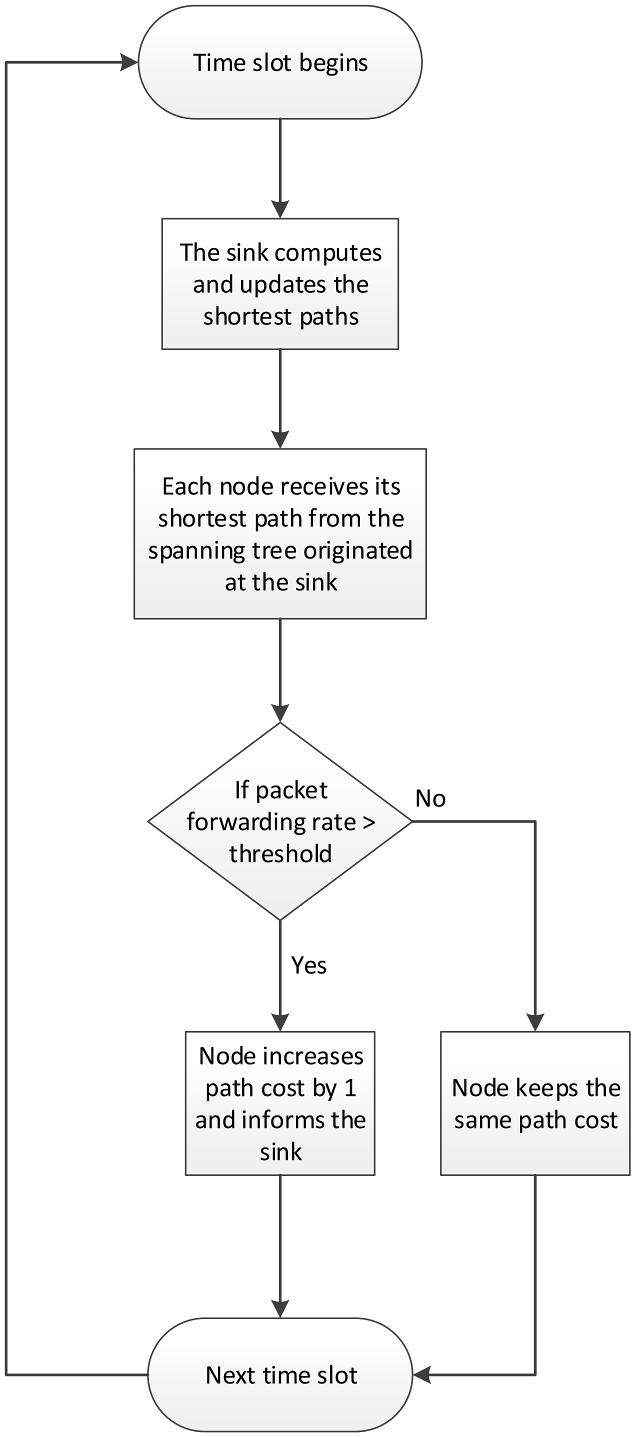

Figure 4. The illustrated flowchart of packet forwarding rate scheme.

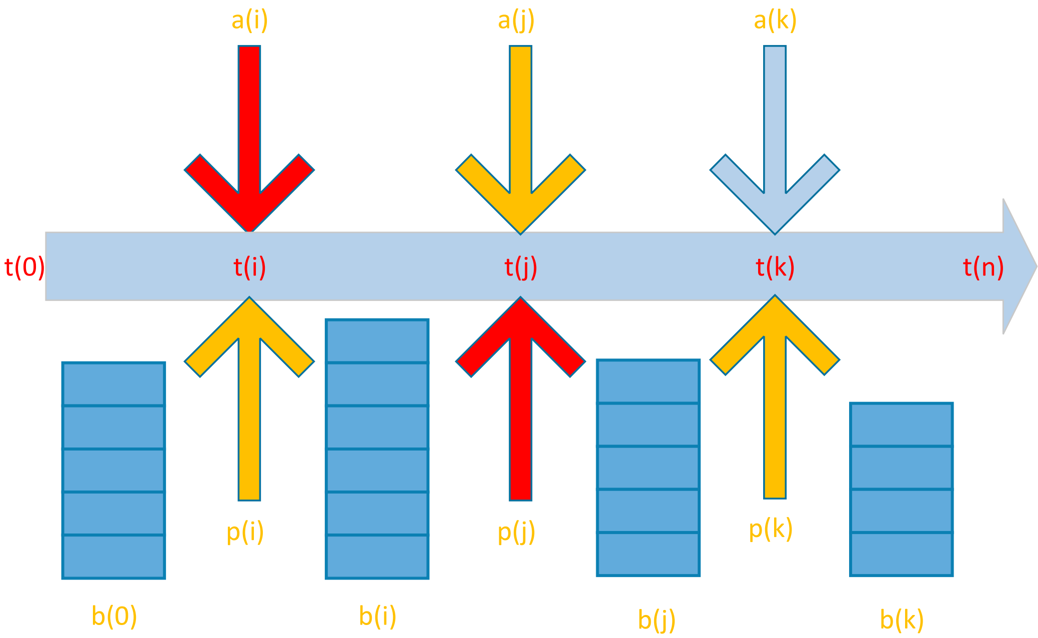

Figure 5. The illustration of the battery charging rate of the energy harvesting scheme.

From Equation (3), the charge rate of the battery capacity unit Δb can be obtained. The Δb represents the deviation of the current battery capacity with the battery capacity in the previous cycle $b(i-1)$. It is also the result of the rate of harvested energy minus the rate of consumed power in each node.

To achieve the immortal WSNs, an additional parameter called battery charging rate Δb is introduced to be the forward awareness factor. If the parameter Δb is greater than 0, it means that the battery of the sensing node is always in the positive charging state and will not be affected by the power consumption of packet transmission. The battery charging rate is the main considering parameter to update the path cost of each node. If the parameter is less than or equal to 0, it means that the power consumption rate of the node is faster than the power charging rate, and the power consumption rate is regarded as the main consideration factor. Therefore, the path cost design of the energy harvesting scheme can be considered together with both the packet forwarding rate and energy harvest rate.

The operation of the forward awareness factor as the path cost of power harvesting scheme can be described as follows. In each time slot, it is required to consider whether the Δb parameter is a positive value. If Δb is greater than 0, the path cost still keeps the same. In contrast, if the charging rate is less than or equal to 0, it is considered to follow the design principle of the first power consumption scheme. When the power consumption rate $p(i)$ in each node is greater than the average power consumption threshold value p_{avg} (i), the path cost is increased by 2. If the $p(i)$ is less than or equal to the $p_{avg}(i)$, the path cost is incremented by 1. The detail design flowchart of the energy harvesting scheme are shown in Figure 6.

In real operation, the extra cost is generated to deploy the energy harvesting device and it will increase some subordinate costs. However, it can effectively extend the lifecycle of the sensing network and eliminate the requirement to replace the battery. To joint consider the energy balanced routing and energy harvesting benefits, the design aim of the immortal WSNs can be achieved when the energy harvesting rate in the hotspots is greater than energy consumption rate for packet transmission.

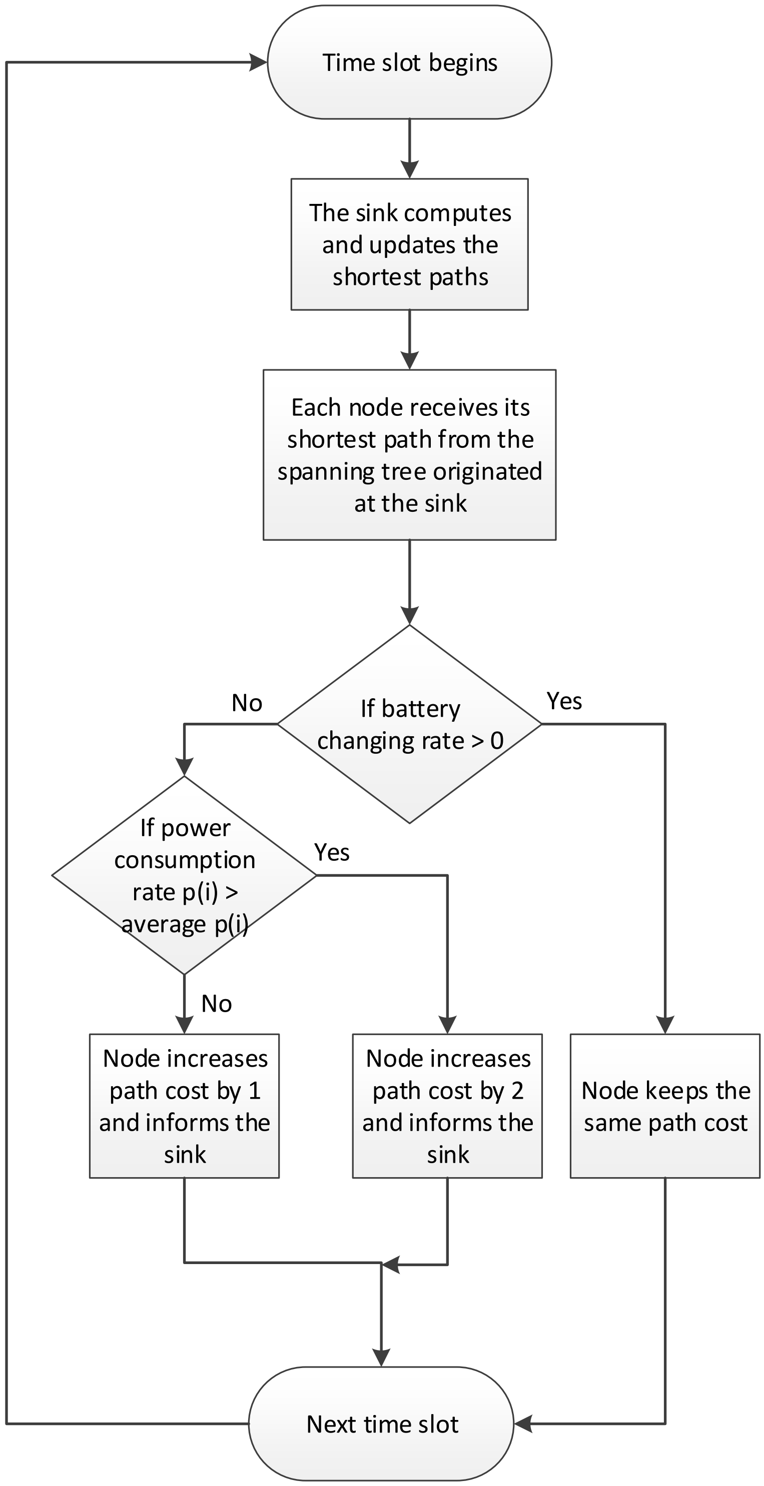

Figure 6. The illustrated flowchart of power harvest scheme.

5. Simulation Results

To validate the effectiveness of the proposed strategy, the network performances of energy routing protocols including the proposed SPT-LBR and the conventional Dijkstra algorithms are both investigated. To estimate the energy routing performances, a two-dimensional planar network with one data sink (Identification, ID 41) and 80 CHs nodes are studied here. The 80 CHs are even distributed in a given operation area and each cluster owns several sensors to detect the cluster area.

The four primary nodes in the SCA are 32, 41, 42, and 50. The SPT-EBR and the Dijkstra algorithms are both applied to compute the shortest paths with various forward awareness factors including the packet forwarding rate and the energy harvesting rate. With regard to the packet transmission, each sensor sends packets to the CHs and each CH fuses data as well as forwards them to the sink periodically. Two performances including the power consumption rate distribution and the network lifetime are compared between the power consumption scheme, power harvesting scheme, and the Dijkstra algorithm.

Figure 7 shows the power consumption rate distribution of the power consumption scheme in the red line and the Dijkstra algorithm in the blue line are both examined. In the Dijkstra algorithm, node 32 has the greediest power consumption compared to the other primary nodes, and is nine times than node 50 in average power consumption. In the power consumption scheme of SPT-EBR, the highest power consumption is at nodes 50, 1.4 times than node 41 in average power consumption. As a result, the power consumption scheme achieves better energy utilization with the load balance factor design. From the perspective on hotspot nodes distribution, the hotspot nodes 14, 23, 32, 40, and 42 are spatially distributed in the inter-layers by the Dijkstra routing. With the assistance of the power consumption scheme, the hotspot nodes can be evenly distributed around the sink connectivity area. In addition, the power consumption rate distribution in each intra-layer is more even than the conventional scheme.

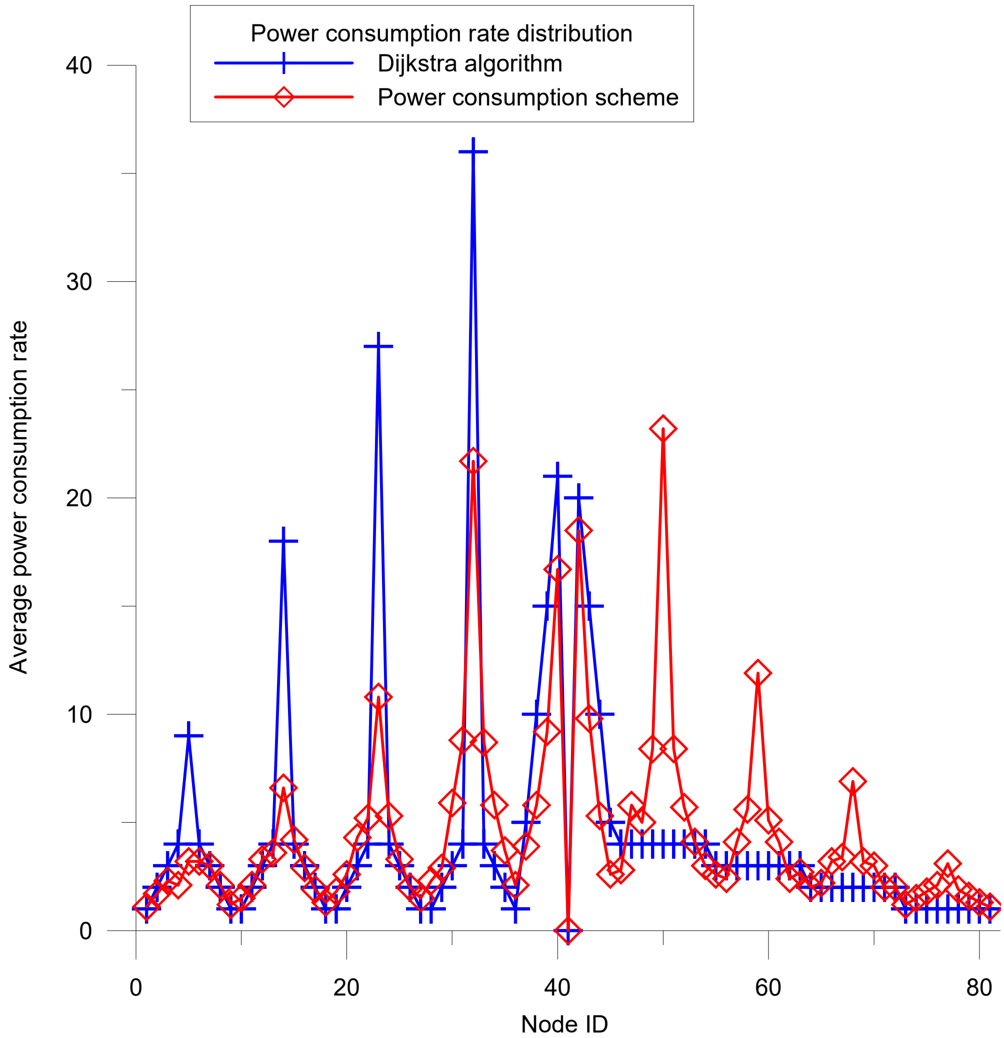

Figure 7. The power consumption rate distribution of the power consumption scheme in Shortest Path Tree with Energy Balance Routing strategy (SPT-EBR).

In Figure 8, the power consumption rate distribution of the larger network with 169 nodes for both the power consumption scheme and the Dijkstra algorithm are investigated. In the Dijkstra algorithm, node 72 encounters the highest power consumption rate than all the other primary nodes and there is 13 times than node 98 in average power consumption. This may lead to an inevitable energy unbalance problem in hotspot nodes as the network size grows. In the power consumption scheme of SPT-EBR, the highest power consumption rate is occurred at nodes 98 and there is 1.56 times than node 86 in average power consumption. With the load balance factor to select the next forwarding node, the power consumption scheme achieves better energy utilization than the Dijkstra algorithm. In addition, the energy unbalance problem can be controlled with the packet forwarding rate factor in the power consumption scheme.

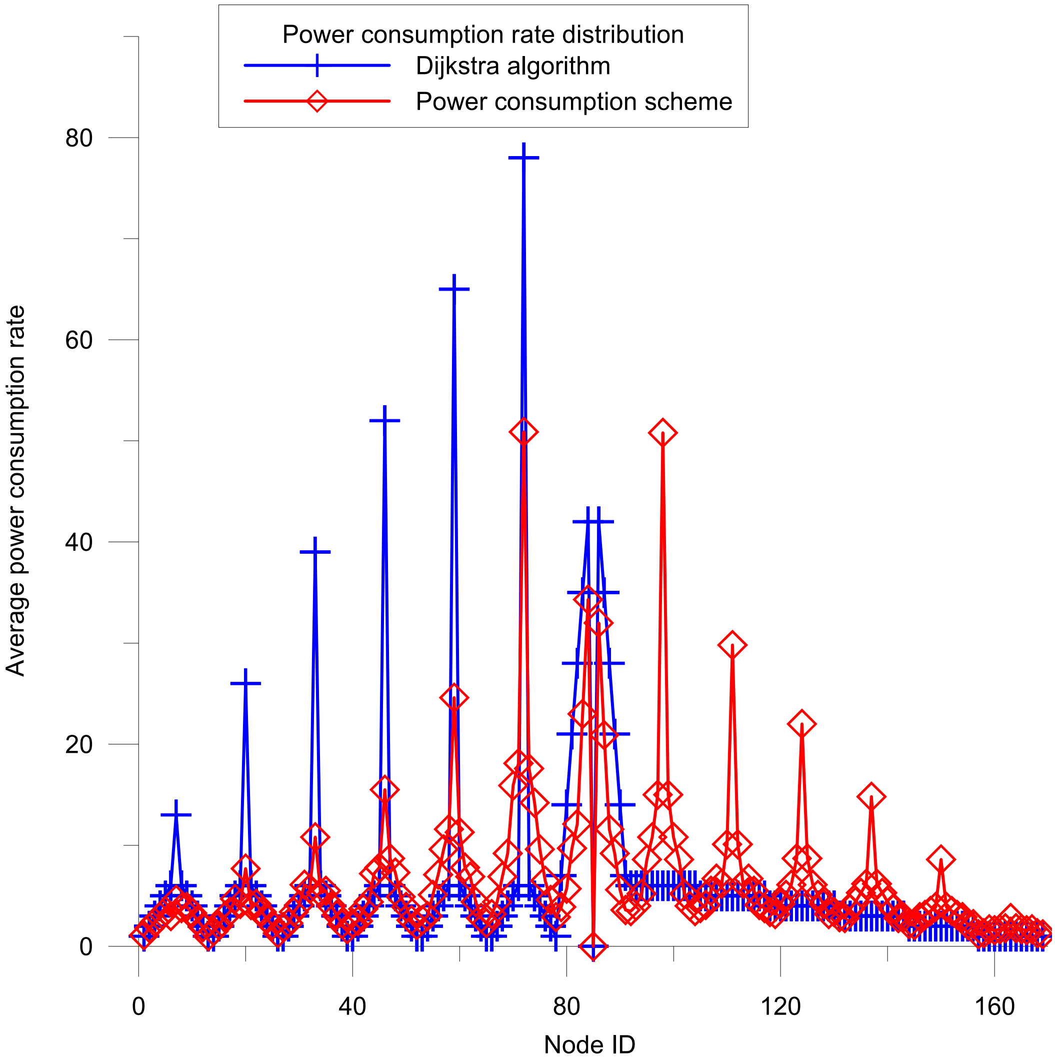

Figure 8. The power consumption scheme for larger SPT-EBR networks.

To evaluate the energy harvesting scheme, a uniform distribution of energy harvesting mode is introduced here to perform the simulation. The energy harvesting strategy includes the full nodes charging and the partial nodes charging strategies. The partial nodes charging strategy is designed to charge the 20% heavy traffic nodes and save the deployment cost in realizing the energy charging. The power charging value is uniformly distributed from 0 to 18 for the energy harvesting scheme and the average battery charging rate of the overall nodes is 7. Figure 9 shows the power consumption rate distribution of the energy harvesting scheme and both schemes achieve the identical power consumption for the four primary hotspot nodes. In general, the full nodes charging method achieves better performance than the partial nodes charging approach for most of the other nodes in power consumption since it spends more operation cost for energy charging.

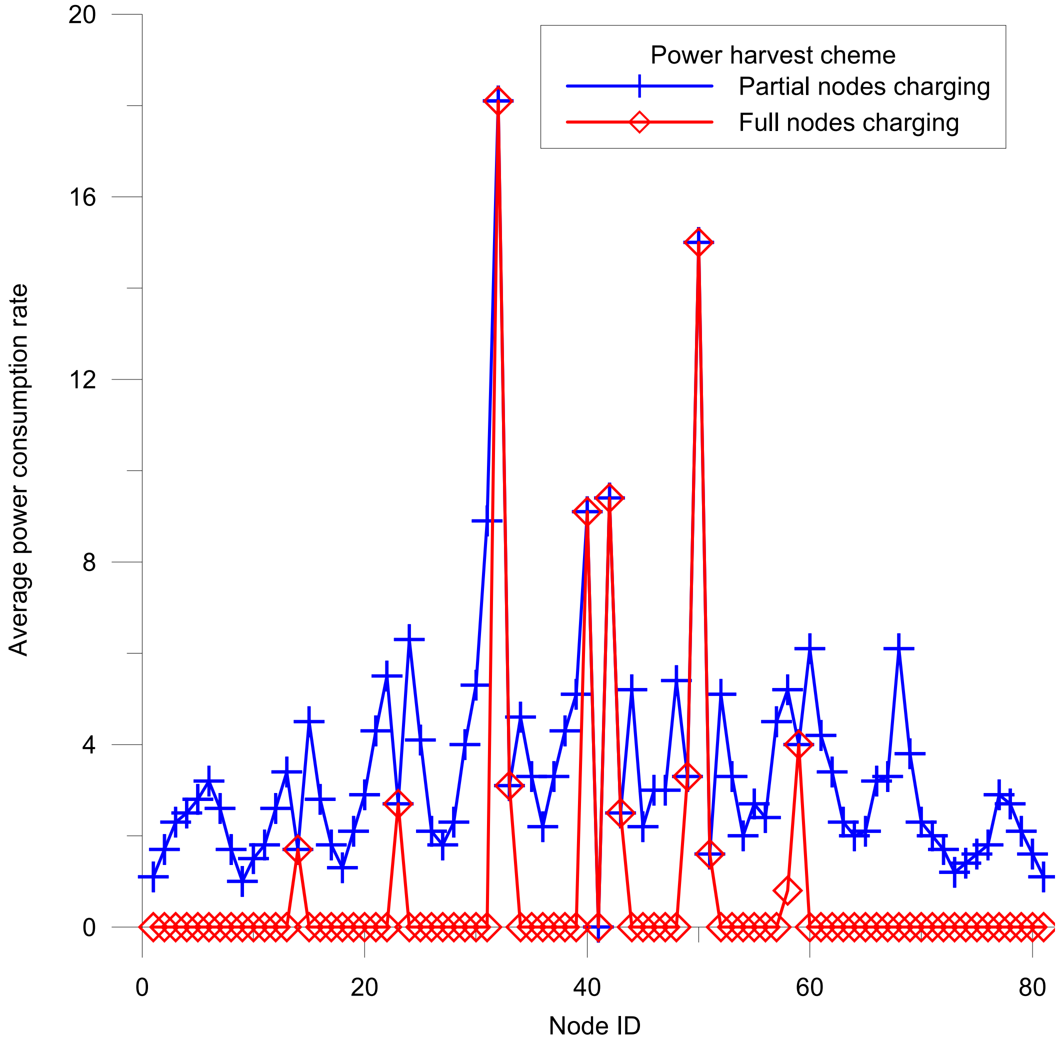

Figure 9. The power consumption rate distribution of the power harvest scheme in SPT-EBR.

For network lifecycle evaluation, the initial energy at each node is set to 0.6 J, and the network lifecycle is evaluated by operation rounds. The energy consumption per transmission bit is 50 nJ/bit and the data is 1000 bits in length [35]. The primary node with the highest power consumption rate is considered as the hotspot, which will limit the overall network lifecycle. Thus, the network lifecycle is inversely proportional to the highest power consumption rate of the hotspot. An additional model, called constant power charging rate is also designed in the energy harvesting scheme to achieve the everlasting WSNs. Figure 10 shows the network lifecycle of both SPT-EBR and Dijkstra algorithms. The power consumption scheme demonstrates an improvement of almost 52% over the Dijkstra scheme, and the power harvest scheme almost doubles the lifecycle than that of the Dijkstra scheme. In addition, the constant power charging rate can extend almost 6.5 times than the Dijkstra scheme in the overall network lifecycle. From the results, it can be concluded that the immortal WSNs can be achieved when the energy harvesting rate is greater than the power consumption rate, especially for the hotspot nodes.

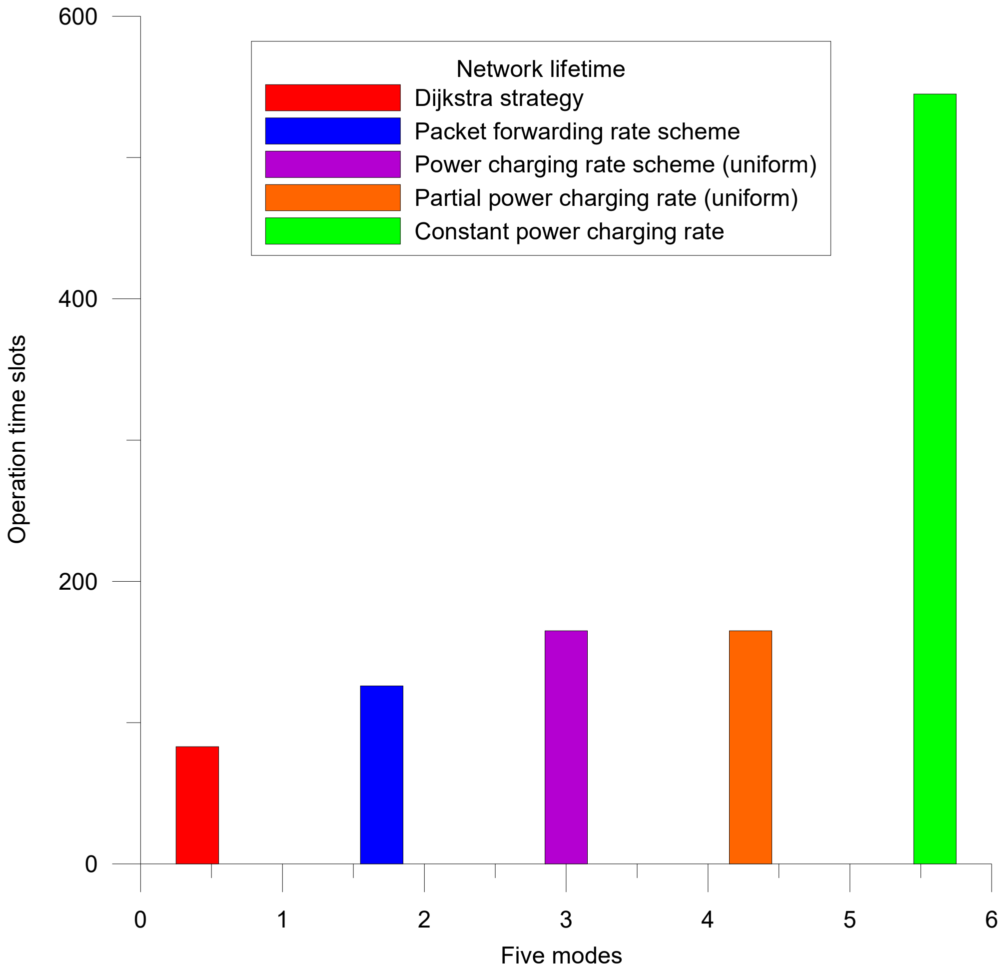

Figure 10. The network lifecycle of SPT-EBR and Dijkstra algorithms.

Figure 11 shows that the battery charging rate Δb of three cases includes the low, the medium and the high charging conditions for the worst hotspot node of packet transmission. The constant charging rate for the low case is 10 units/round, the medium case is 20 units /round, and the high case is 30 units/round. The high battery charging rate case achieves the best energy harvesting performance since the deployment cost is the highest. Because the parameter Δb is greater than 0 in the high charging rate case, it means that the battery of the worst sensing node is always in the positive charging state and will not be affected by the power consumption of packet transmission. In other words, the immortal WSNs can be achieved by control the positive charging rate for the worst hotspot node during packet transmission. In addition, the peak power consumption rate is 36/27/18/9 for the four intra-layers from the sink for the conventional scheme (blue curve) and is 23.2/11.9/6.9/3.9 for the SPT-EBR scheme in Figure 7, respectively. The peak power consumption rate means that the minimum charging power for each layer and thus the proposed method can save the charging power about 55.7% in average in each operation round.

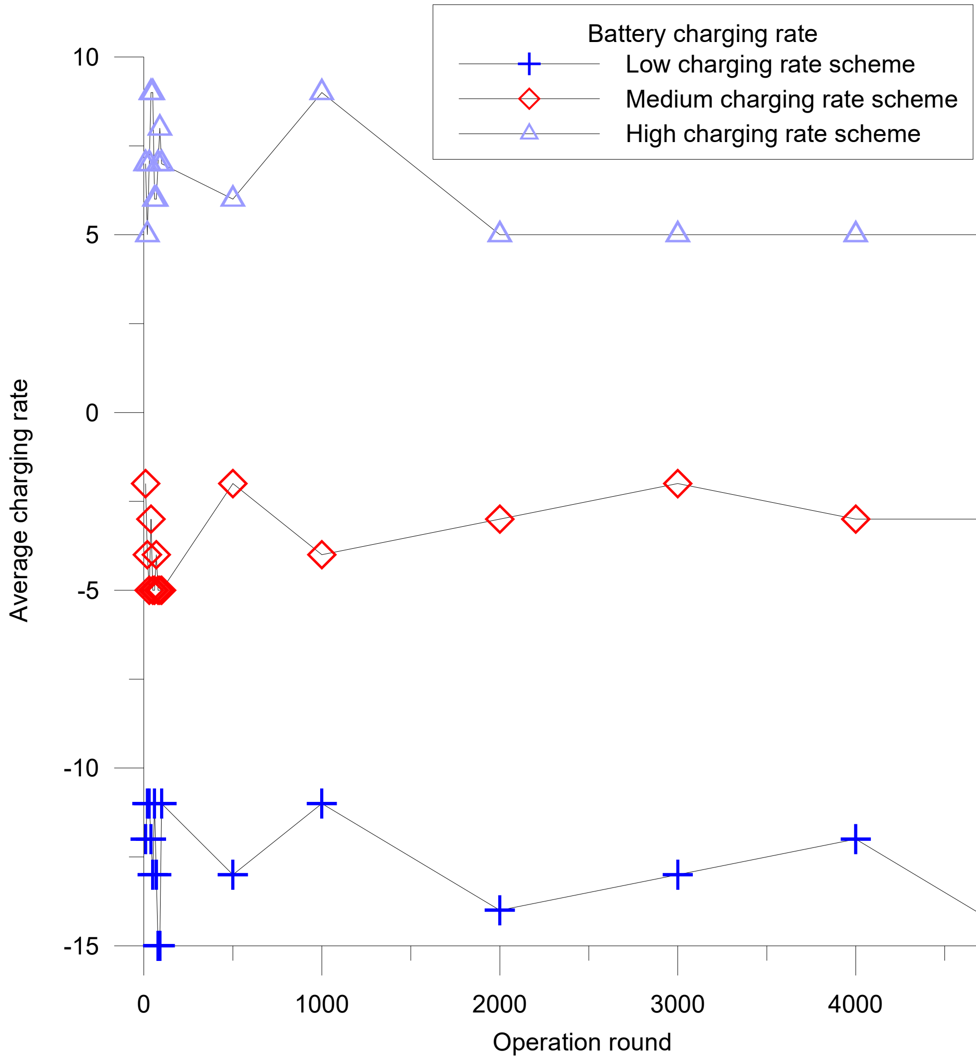

Figure 11. The battery charging rate of the worst hotspot node for SPT-EBR.

Figure 12 shows the routing computation cost of power consumption scheme and energy harvesting scheme in the SPT-EBR and the Dijkstra algorithm. It can be observed that the Dijkstra algorithm achieves the least computation time to make the routing path convergence. To achieve lower power consumption rate and higher network lifecycle, the power consumption scheme spends additional 34% time cost for balanced routing computation. In the energy harvesting scheme, three strategies including the full nodes harvesting, the partial nodes harvesting and the constant harvesting achieve better network lifecycle extension but spends additional 72% time cost to generate the balanced routing paths. From the above results, it is better to spend routing computation cost in the early period rather than the late-remedy strategy in the maintenance phase to extend the network lifecycle.

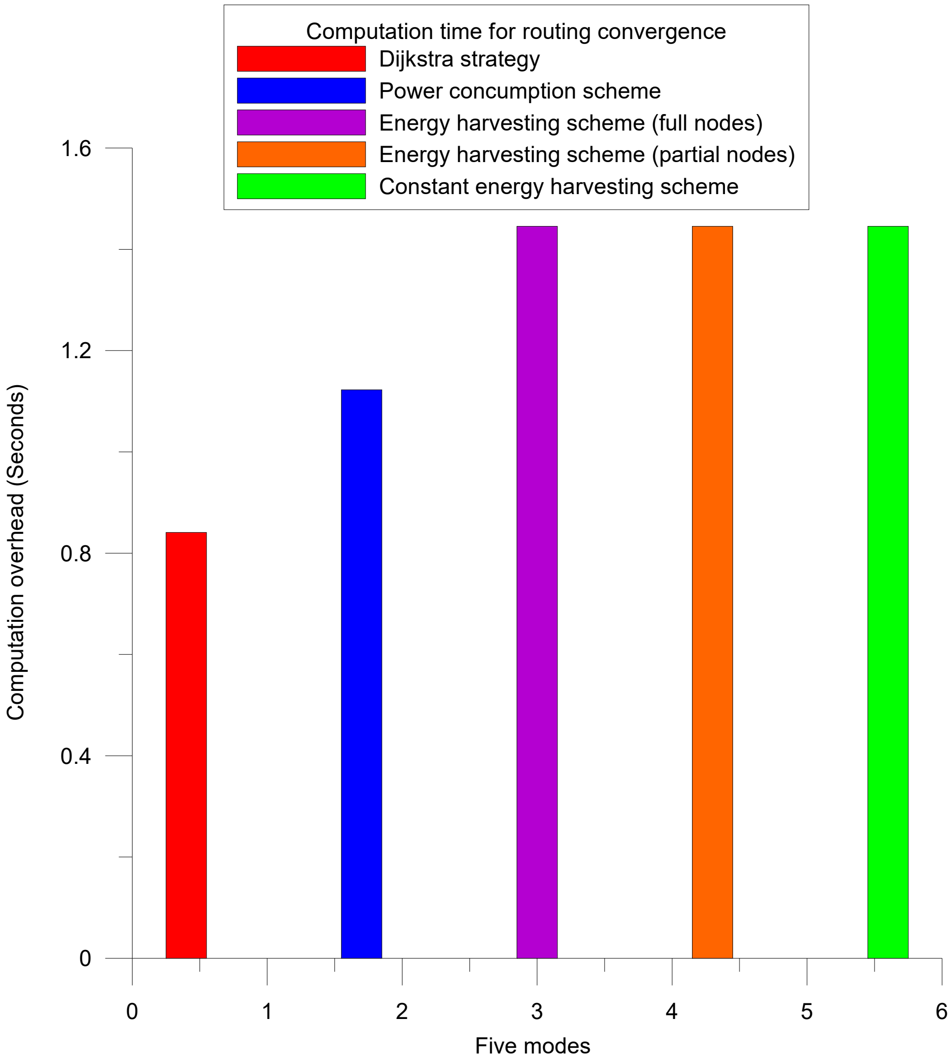

Figure 12. The routing computation cost of SPT-EBR and Dijkstra algorithms.

6. Conclusions

To joint consider the energy balanced routing and energy harvesting benefits, a Shortest Path Tree with Energy Balance Routing strategy (SPT-EBR) is proposed in the article. In SPT-EBR, two methods are presented, including the power consumption and the energy harvesting schemes to select the forwarding node according to the awareness factors of link weight. First, the packet forwarding rate factor was considered in the power consumption scheme to update the link weight for the sensors with higher power consumption and mitigate the traffic load of hotspot nodes to achieve the energy balance network. Then, the energy harvesting scheme combines both the packet forwarding rate and the power charging rate factors together to update the link weight with a new battery charging rate factor for the hotspots. Finally, simulation results validate that both power consumption and energy harvesting schemes in SPT-EBR achieve better energy balance performance and save more charging power than the conventional shortest path protocol and thus improve the overall network lifecycle. Additionally, it can also be inferred that the immortal WSNs has a high probability to be realized when the energy harvesting rate is greater than the power consumption rate especially for the hotspot nodes. As a result, the design aim of immortal WSNs can be achieved, which profits from the effective harvested energy and load balanced routing strategy.

Author Contributions: C.-M.Y. designed the joint balanced routing and energy harvesting strategy with power consumption and energy harvesting schemes including the corresponding algorithms. M.T. helps to investigate

the related work and validates the simulation performances. C.-H.C. and C.-Y.H. performed the simulation and analyzed the results.

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References

1. Xu, L.; Collier, R.; O'Hare, G.M.P. A Survey of Clustering Techniques in WSNs and Consideration of the Challenges of Applying Such to 5G IoT Scenarios. *IEEE Internet Things J.* **2017**, *4*, 1229–1249. [CrossRef]
2. Gungor, V.C.; Lu, B.; Hancke, G.P. Opportunities and challenges of wireless sensor networks in smart grid. *IEEE Trans. Ind. Electron.* **2010**, *57*, 3557–3564. [CrossRef]
3. Ruiz-Garcia, L.; Lunadei, L.; Barreiro, P.; Robla, I. A review of wireless sensor technologies and applications in agriculture and food industry: State of the art and current trends. *Sensors* **2009**, *9*, 4728–4750. [CrossRef] [PubMed]
4. Gisbert, J.R.; Palau, C.; Uriarte, M.; Prieto, G.; Palazón, J.A.; Esteve, M.; López, O.; Correas, J.; Lucas-Estañ, M.C.; Giménez, P.; et al. Integrated system for control and monitoring industrial wireless networks for labor risk prevention. *J. Netw. Comput. Appl.* **2014**, *39*, 233–252. [CrossRef]
5. Xin, H.; Liu, X. Energy-Balanced Transmission with Accurate Distances for Strip-Based Wireless Sensor Networks. *IEEE Access* **2017**, *5*, 16193–16204. [CrossRef]
6. Yan, J.; Zhou, M.; Ding, Z. Recent Advances in Energy-Efficient Routing Protocols for WirelessSensor Networks: A Review. *IEEE Access* **2016**, *4*, 5673–5686. [CrossRef]
7. Gungor, V.C.; Hancke, G.P. Industrial wireless sensor networks: Challenges, design principles, and technical approaches. *IEEE Trans. Ind. Electron.* **2009**, *56*, 4258–4265. [CrossRef]
8. Dietrich, I.; Dressler, F. On the lifetime of wireless sensor networks. *ACM Trans. Sens. Netw.* **2009**, *5*, 1–39. [CrossRef]
9. Zhang, D.; Li, G.; Zheng, K.; Ming, X. An energy-balanced routing method based on forward-aware factor for wireless sensor networks. *IEEE Trans. Ind. Inform.* **2014**, *10*, 766–773. [CrossRef]
10. Pantazis, N.A.; Nikolidakis, S.A.; Vergados, D.D. Energy-effcient routing protocols in wireless sensor networks: A survey. *IEEE Commun. Surv. Tutor.* **2013**, *15*, 551–591. [CrossRef]
11. Guo, W.; Zhang, W. A survey on intelligent routing protocols in wireless sensor networks. *J. Netw. Comput. Appl.* **2014**, *38*, 185–201. [CrossRef]
12. Chang, J.-H.; Tassiulas, L. Maximum lifetime routing in wireless sensor networks. *IEEE/ACM Trans. Netw.* **2004**, *12*, 609–619. [CrossRef]
13. Gupta, H.P.; Rao, S.V.; Yadav, A.K.; Dutta, T. Geographic routing in clustered wireless sensor networks among obstacles. *IEEE Sens. J.* **2015**, *15*, 2984–2992. [CrossRef]
14. Amini, N.; Vahdatpour, A.; Xu, W.; Gerla, M.; Sarrafzadeh, M. Cluster size optimization in sensor networks with decentralized cluster-based protocols. *Comput. Commun.* **2012**, *35*, 207–220. [CrossRef]
15. Han, Z.; Wu, J.; Zhang, J.; Liu, L.; Tian, K. A general self-organized tree-based energy-balance routing protocol for wireless sensor network. *IEEE Trans. Nucl. Sci.* **2014**, *61*, 732–740. [CrossRef]
16. Yu, C.M.; Ku, M.L. Joint Hybrid Transmission and Adaptive Routing for Lifetime Extension of WSNs. *IEEE Access* **2018**, *6*, 21658–21667. [CrossRef]
17. Yetgin, H.; Cheung, K.T.K.; El-Hajjar, M.; Hanzo, L. A Survey of Network Lifetime Maximization Techniques in Wireless Sensor Networks. *IEEE Commun. Surv. Tutor.* **2017**, *19*, 828–854. [CrossRef]
18. Liu, X. Routing Protocols Based on Ant Colony Optimization in Wireless Sensor Networks: A Survey. *IEEE Access* **2017**, *5*, 26303–26317. [CrossRef]
19. Ogundile, O.O.; Alfa, A.S. A Survey on an Energy-Efficient and Energy-Balanced Routing Protocol for Wireless Sensor Networks. *Sensors* **2017**, *17*, 1084. [CrossRef]
20. Sudevalayam, S.; Kulkarni, P. Energy harvesting sensor nodes: Survey and implications. *IEEE Commun. Surv. Tutor.* **2011**, *13*, 443–461. [CrossRef]
21. Ulukus, S.; Yener, A.; Erkip, E.; Simeone, O.; Zorzi, M.; Grover, P.; Huang, K. Energy harvesting wireless communications: A review of recent advances. *IEEE J. Sel. Areas Commun.* **2015**, *33*, 360–381. [CrossRef]
22. Lu, X.; Wang, P.; Niyato, D.; Kim, D.I.; Han, Z. Wireless charging technologies: Fundamentals, standards, and network applications. *IEEE Commun. Surv. Tutor.* **2016**, *18*, 1413–1452. [CrossRef]

23. Du, R.; Ozcelikkale, A.; Fischione, C.; Xiao, M. Optimal energy beamforming and data routing for immortal wireless sensor networks. In Proceedings of the 2017 IEEE International Conference on Communications (ICC), Paris, France, 21–25 May 2017.
24. Cheng, D.; Xun, Y.; Zhou, T.; Li, W. An energy aware ant colony algorithm for the routing of wireless sensor networks. In *Intelligent Computing and Information Science (Communications in Computer and Information Science)*; Springer: Berlin, Germany, 2011; Volume 134, pp. 395–401.
25. Luo, J.; Hu, J.; Wu, D.; Li, R. Opportunistic routing algorithm for relay node selection in wireless sensor networks. *IEEE Trans. Ind. Inform.* **2015**, *11*, 112–121. [CrossRef]
26. Kumar, V.; Kumar, S. Energy balanced position-based routing for lifetime maximization of wireless sensor networks. *Ad Hoc Netw.* **2016**, *52*, 117–129. [CrossRef]
27. Kulshrestha, J.; Mishra, M.K. An adaptive energy balanced and energy efficient approach for data gathering in wireless sensor networks. *Ad Hoc Netw.* **2017**, *54*, 130–146. [CrossRef]
28. Liu, L.; Zhang, R.; Chua, K.-C. Multi-antenna wireless powered communication with energy beamforming. *IEEE Trans. Commun.* **2014**, *62*, 4349–4361. [CrossRef]
29. Xu, J.; Zhang, R. A general design framework for MIMO wireless energy transfer with limited feedback. *IEEE Trans. Signal Process.* **2016**, *64*, 2475–2488. [CrossRef]
30. Zeng, Y.; Clerckx, B.; Zhang, R. Communications and signals design for wireless power transmission. *IEEE Trans. Commun.* **2017**, *65*, 2264–2290. [CrossRef]
31. Du, R.; Ozcelikkale, A.; Fischione, C.; Xiao, M. Towards Immortal Wireless Sensor Networks by Optimal Energy Beamforming and Data Routing. *IEEE Trans. Wirel. Commun.* **2018**, *17*, 5338–5352. [CrossRef]
32. Singh, K.; Ku, M.L.; Lin, J.C. Joint power control and energy transfer for energy harvesting relay networks. In Proceedings of the 2016 IEEE International Conference on Communications (ICC), Kuala Lumpur, Malaysia, 22–27 May 2016.
33. Singh, K.; Ku, M.L.; Lin, J.C.; Ratnarajah, T. Toward Optimal Power Control and Transfer for Energy Harvesting Amplify-and-Forward Relay Networks. *IEEE Trans. Wirel. Commun.* **2018**, *17*, 4971–4986. [CrossRef]
34. Gupta, A.; Singh, K.; Sellathurai, M. Time-Switching EH-Based Joint Relay Selection and Resource Allocation Algorithms for Multi-User Multi-Carrier AF Relay Networks. *IEEE Trans. Green Commun. Netw.* **2019**, *3*, 505–522. [CrossRef]
35. Wu, D.; He, J.; Wang, H.; Wang, C.; Wang, R. A hierarchical packet forwarding mechanism for energy harvesting wireless sensor networks. *IEEE Commun. Mag.* **2015**, *53*, 92–98. [CrossRef]