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# A kind of novel VPF-based energy-balanced routing strategy for wireless mesh network

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SUMMARY

Wireless mesh network (WMN) can sense information and realize end-network transmission. It consists of numerous wireless sensors, the energy and communication ability of which are limited. A kind of novel VPF-based energy-balanced routing strategy for WMN has been presented in this paper. Most of the existing energy-efficient routing strategy always forwards packets along the minimum energy path to the sink to merely minimize energy consumption, which causes an unbalanced distribution of residual energy among sensor nodes, and eventually results in a network partition. We design the energy-balanced routing strategy by setting up a mixed virtual potential field in terms of depth and energy by using the physical potential concept. The strategy can force packets to move toward the sink through the dense energy area and protect the nodes, which has relatively low residual energy. By comparing to the other energy-efficient routing strategy in our designed scenarios, the experimental results show that energy balance and throughput can be improved. Copyright © 2014 John Wiley & Sons, Ltd.

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KEY WORDS: WMN; energy; VPF; routing; balance

## 1. INTRODUCTION

Energy saving is a critical issue in wireless mesh networks (WMN) because their nodes are battery-powered. WMN are deployed for a variety of industrial applications, such as mobile services, environmental monitoring, ocean protection, battlefield surveillance, and so on [1, 2]. An unreliable wireless communication environment and limited energy resources have a severe impact on the QoS of WMN. Energy is one of the most important resources for the battery-powered WMN. How to prolong the lifetime of WMN powered by finite battery energy is a hot research challenge. For extending the network lifetime as much as possible, the effectiveness of the energy becomes one of the basic principles in the design of WMN protocol.

For utilizing the limited available powder of sensor nodes more effectively, most of the current routing scheme tries to find the path with minimum energy consumption in order to save energy and optimize the energy use of nodes. However, there is a problem that whether it is adequate to only focus on the efficiency of energy or that some objectives such as lifetime of network and communication coverage should also be considered. In [3, 4], the scholars suggest the property of energy balance, then analyze or evaluate an energy-balanced algorithm, whereas the hypothesis is

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unrealistic for multi-hop WMNs that the nodes can directly contact the sink node. In [5, 6], the energy holes close to the convergence node are taken into account without taking balance of energy consumption into consideration.

As we know, an energy-aware routing method should put the energy-balanced consumption as target instead of the energy efficiency. In addition, according to the requirements of application, the routing methods in WMN may be naturally divided into two categories: search-based data routing method and acquisition-based data routing method. The first one spreads some interesting news in order to induce query to realize the path to the event. The second one seeks the appropriate path from the sensor nodes to the sink node to collect the data.

Data aggregation is an effective strategy to save energy because the number of transmissions can be reduced after aggregation. Reference [4, 7] strives for energy balancing to make the network lifetime maximum. The unbalanced consumption of energy is harmful to network safety and health. If the sensor nodes of WMN spend their energy in a relative balanced way, the connectivity among sensor nodes and the sink nodes can be kept for a longer time, and making the network segmentation to be postponed. The degradation of more smoothly of network coverage can obviously provide considerable benefits. Thus, it is reasonable and useful to keep necessary trade-offs between energy consumption and network lifetime of WMN. In order to achieve energy consumption keep equilibrium, a non-uniform node distribution strategy is presented in [8, 9]. However, its cost is quite large, because not only the outer corona, but also the number of nodes from external corona to internal corona increases in geometric progression. Based on improving the viability of the network, the energy-aware routing in [10, 11] routes and keeps several paths and selects one of them appropriately.

The concept of physical gradient and physical potential is not only used in WMN, but also applied to the wired network. As we know, one traffic sensing routing algorithms named PBTA [12–14] has been proposed to transmit data packets along the hot spots, which is congested in WMN, thus shortening the end-to-end delay. But it did not cause much concern due to its huge administrative costs. In traditional networks, each node in a random deployment may be the destination node of some data packets [15–17].

In this paper, we will propose a new routing strategy, which can overcome most of the problem of unbalanced energy occupation in many existed energy-saving routing methods and improve the advantage of energy-balanced consumption in the whole WMN of certain area. Based on classical potential field (PF) theory of physics, we present an energy-balanced data collection routing strategy. It is named the energy-balanced routing protocol (EBRP). Through the intensive energy region, it forwards the packet to the sink node so as to protect the sensor nodes, which have low residual energy (RE).

## 2. RELATED WORKS

Although many energy-aware routing algorithms were designed in the relative literature, many of them only care a certain aspect of network performance, such as energy efficiency, which is to find the best path to save energy consumption [1, 2]. As mentioned earlier, many papers focus on energy-saving routing strategy, which aims to find an optimal path to reduce the energy consumption in the local nodes or in the whole WMN as soon as possible. However, some of the existing routing methods have been discovering the energy imbalance problem. As we know, low energy adaptive clustering hierarchy (LEACH) [3, 4] and energy efficient uneven clustering [5, 6] provided energy balance function in the cluster through selecting cluster randomly, but only a partial solution can be solved.

Many energy-balanced data fusion strategies are based on a structured architecture to do data gathering. Such structure-based strategies need high maintenance overhead in some dynamic environments. Reference [2] proposed a structure-free and energy-balanced data integration strategy named SFEB. The SFEB has the features including efficient data gathering, balanced energy occupation, which supports by the two-phase integration processing and its dynamic fusing selection strategy.

In order to make network performance of WMN improved, an energy-balanced cooperative media access control (EBCMAC) strategy is proposed in Reference [3]. It uses the optimal partnership

 
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selection method by opportunistic relaying to select the cooperative node with the optimal channel conditions, the optimal transmission rate, and balanced energy occupation. The experimental results of EBCMAC, Cooperative MAC, and IEEE 802.11 distributed coordination function strategy show that EBCMAC outperforms the other two strategies covering the packet delivery ratio, network throughput, and network lifetime under two distinct channel noise levels.

In order to balance energy consumption, Reference [4] proposed a new strategy considering five factors in a cross layer fashion (EBCL): the wireless channel condition, the physical layer channel coding redundancy, the application layer traffic rate, the path-level energy balancing of the network, and the QoS of data transmission. In this kind of strategy, it developed an optimal scheme to allocate path-level traffic of data packets and link level channel coding redundancy jointly, which minimizes battery energy consumption of the routers while satisfying a lower bound of quality requirement. The experimental results show that this kind of strategy can significantly improve the energy balancing of the WMN by realizing the traffic and channel coding control for energy consumption.

An attentive multipath routing method has been proposed to get energy-balanced space in Reference [12, 13, 15]. In Reference [16], the balance of energy consumption can be achieved by switching between two transmission paradigms: direct transmission paradigm and multi-hop transmission paradigm. The first transmission paradigm can reduce the energy consumption of sensor nodes near the sink node, because the relay energy consumption can be low in this paradigm. The second transmission paradigm can reduce the energy consumption of sensor nodes far away from the sink node. As we know, EBDG [18] makes full use of network partition to make the energy consumption be balanced.

Gradient-Based Routing (GBR) [11, 19] is a kind of the shortest path routing, because only the hop count is considered in the process of calculating the gradient. GBR dispatches traffic of data packets among all sensor nodes and balances non-uniform communication overload. The sink node of WMN broadcasts a message of the internet, which may be flooded among the whole WMN. Each node of WMN receives the message and records the hop-count information carried by the message to calculate the number of hops from the sensor node to the sink node in certain area [20, 21]. The gradient between the sensor node to the sink node is the difference among the hop-counts. Many gradient-based information query routing methods [21, 14] use the physical gradient, which is just like that the spatial distribution of many physical quantities (such as the temperature measured by thermal sensor) obey the natural diffusion law. In order to overcome this drawback, we calculate the discrete approximation of partial differential equations on the appropriate online neighbors to get the informational potential.

The previous researches showed that the nodes near sink node will deplete their energy faster than other nodes [3, 17]. This unbalanced consumption of energy greatly reduces the lifetime and coverage of the network. In addition, the result in [22, 23] shows that when the nodes that are a hop away from sink node run out of energy, those at greater distance has still 90% of the remaining initial energy.

Our suggested solution on EBRP by constructing a virtual PF (VPF-EBRP) adopts the sharpest gradient searching approach for making decision of the routing. There are several gradient-based routing methods in WMN. The key insight of the energy-balanced routing strategy is to build separate VPFs in the aspect of depth and energy. In this strategy, the depth field can be used as a part of routing mode, which can keep the data packet moving toward the sink node. The energy field can be used to ensure that the data packet is often transmitted by the high-energy region and keep a long lifetime for low-energy nodes. The final routing decision will be made based on integrated VPFs, which considers depth field and energy field.

## 3. VPF-BASED ENERGY-BALANCED ROUTING STRATEGY

We describe and propose the idea of program VPF-EBRP in this section. We explain how to use energy, depth on each node to build PF, and how they are combined with a single unified VPF to drive the data packets moving to sink node while balancing energy occupation.



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### *3.1. Principle of the VPF-EBRP*

For the routing method design in WMN, energy balance and energy efficiency will lead to routing strategy with different properties. A routing protocol with high efficiency and energy saving tries to minimize the energy consumption to extend the lifetime of the network, whereas an energy-balanced routing method can help to make the network lifetime longer by using the energy in a balanced way. Although there may still exist a lot of RE, the former is easy to cause an early network partition, which can make the network stop working. On the other hand, in respect of energy efficiency, the latter may not be optimal, but it can balance the energy consumption to maintain the network connectivity and keep the network running at a longer time. An example can be setup to show the results result from unbalanced energy consumption and how the program VPF-EBRP balances the energy consumption. The topology cases of WMN are shown in Figure 1. Assuming an event occurs in a certain area, it may be very far away from the sink node. Many of the existing energy-saving routing protocol is easy to select the shortest path, because only two-hops can be reached, the sink node and the energy consumption is minimized.

In order to balance the energy occupation between each area of WMN, because the energy density (ED) of the specified area is as high as those of other areas, VPF-EBRP will select the routing; its algorithm is same as most energy-efficient routing algorithm. However, after a period when the RE of sensor nodes in the specified area is lower than those in other regions, VPF-EBRP can route data packets form area A by area B with more nodes and energy before the energy of nodes in the specified area is depleted. So the specified area is properly controlled. In this mode, the energy balance and energy efficiency can be considered, thereby getting reliable results. The main question is how to dynamically select between different probable paths according to the local available information.

Based on the classical physics potential, we can intentionally create one VPF by using a variety of information on each sensor node, so 'pushing' the data packets to the sink node naturally through intensive energy region. In order to prove this novel idea, we setup one VPF by adopting the energy in a WMN, the sensor nodes close to the center of this WMN is intensive, but the sensor nodes at the edge is sparse. The energy PF of the Figure 1 depicted in the Figure 2 looks like a little mountain. If data packets can often 'climb' to the top of this kind of mountain according to the gradient direction, it can arrive at the sink node in the center of this area. The energy is used for the transmission of data packet and some operations, so the PF is changing with time. The relative potential-based routing is correspondingly changed, it means that the energy use and occupation is balanced. In practice, due to the random topology case and heterogeneous sensor nodes, it is difficult to build and keep such a perfect PF depicted in the Figure 2. We need to establish an available PF by using most of the valuable information.

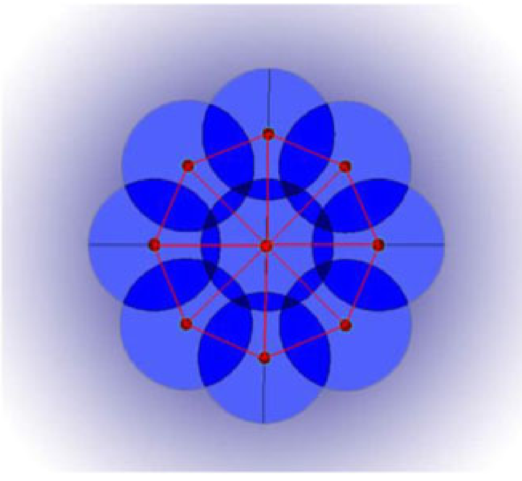

Figure 1. The topology example of wireless mesh network.

 

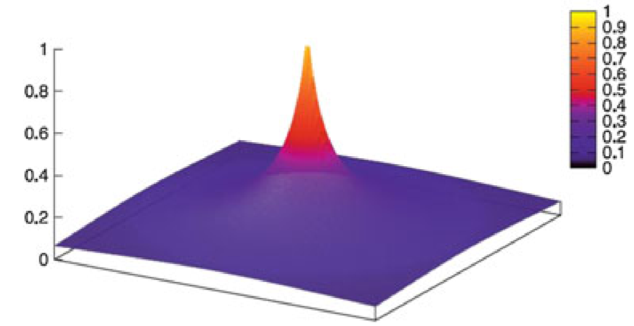


Figure 2. The potential field schematic of virtual potential field energy-balanced routing protocol.

### *3.2. Potential field design*

Because WMN requires very frequent exchange routing information to obtain appropriate routing metrics, it may also be a large overhead. Several data-collected routing methods adopt physical gradient. For the convenience of discussion, we begin with a review of some concepts of classical physics potential theory by one sample of the electric field. These ideas include the potential, the PF, the field strength (FS), the potential difference (PD), the differential coefficients in all directions, and the gradients [14].

The direction of the FS is similar to the direction of the gradient, which means that the negative charge is asked to move forward according to the gradient direction, the direction of the gradient is that the direction of the electric potential (EC) changes the fastest. The direction of the FS is the same as the direction of the strength to withstand the negative charge.

The gradient is the largest differential coefficient in a certain direction, which may be expressed as the PD ratio and distance between the two sensor nodes (points), it is the potential model adopted by the energy balancing routing algorithm designed by us. Thus, if the differential coefficient in all directions among its neighboring points of WMN is known, we can get the gradient of this sensor node. In particular, if the strength from a certain node to its neighboring nodes is negative, then the neighboring node of the greatest strength will be chosen the next hop.

Taking into account the complexity and diversity of WMN, we use the depth, the ED, and the RE to define three different PF, and then put them together to get a mixed superposition PF, thus inducing the data packets moving to the sink node and maintaining the remaining energy evenly. In this way, a network segmentation carried out by energy hole may be delayed, and the survival time of the network may be lengthened. These parameter fields [14] have their different properties, and have different effects on making routing decisions.

(1) *Energy PF* (*EPF*)

If each node makes up the energy value of its all neighbors added, these energy values may be exchanged between the nodes and calculated the area of the disc area covered by the radio in order to easily acquire the corresponding ED. VPF-EBRP defines the EPF as follows:

$$V_e(i,t) = E(i,t) \tag{1}$$

Here, $V_e(i,t)$ is the EP of node $i$ at time $t$, and $E(i,t)$ is the energy function in the position of node $i$ at time $t$ So, the PD $U_e(i,j,t)$ from node $i$ to node $j$ at time $t$ is defined by the following formula:

$$U_e(i,j,t) = V_e(j,t) - V_e(i,t) = E(j,t) - E(i,t) \tag{2}$$

Based on this PF, the data packets often flow from the current sensor node to the area of energy-intensive. Furthermore, in order to protect the nodes with low energy (especially the node in the path to the area of energy-intensive), an additional PF about energy value can be set up.



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(2) *Depth PF* (*DPF*)

In order to provide basic routing functions and induce the data packets to transmit from the sensor node to the sink node, the inverse function of depth can be defined as the DPF $V_d(p)$:

$$V_d(p) = 1/(p+1) \tag{3}$$

Here, $p = D(i)$ represents the depth of node $i$. Then, the depth PD $U_d(p_1, p_2)$ from the depth $P_1$ to the depth $P_2$ is given by the following formula:

$$U_d(p_1,p_2) = V_d(p_2) - V_d(p_1) = 1/(p_2+1) - 1/(p_1+1) \tag{4}$$

Because the potential function is decreasing in monotonic mode, when the data packets in the DPF moves along the gradient direction, the data packets will eventually be able to arrive at the sink node, and the routing process may be finished. In specified network deployment of WMN, $V_d(p)$ is certain and time-invariant. In addition, if data packet moves closer to the sink node, its centripetal force should be more, which means the tendency that the node in depth $d$ transmits data packet to neighboring nodes in depth $d-1$.

(3) *Integrated PF* (*IPF*)

Defined different PFs should be added together to influence the selection of an appropriate route. We normalized the depth and the remaining energy field:

$$U_d^{'}(i,j) = \begin{cases} 1 - \dfrac{1}{\phi_d(i,j)}, \text{if } \ \phi_d(i,j) \geq 1 \\ \phi_d(i,j) - 1, \text{if } \ 0 \leq \phi_d(i,j) < 1 \end{cases} \tag{5}$$

$$U_e^{'}(i,j,t) = \begin{cases} 1 - \dfrac{1}{\phi_e(i,j,t)}, \text{if } \ \phi_e(i,j,t) \geq 1 \\ \phi_e(i,j,t) - 1, \text{if } \ 0 \leq \phi_e(i,j,t) < 1 \end{cases} \tag{6}$$

Here, $\phi_d(i,j) = \frac{V_d(j)}{V_d(i)}$, but $\phi_e(i,j) = \frac{E(j,t)}{E(i,t)}$. The meaning of mopping defined in (5) and (6) that $U_e^{'}(i,j,t)$ and $U_d^{'}(i,j,t)$ represent per unit of the PD of remaining energy potential and depth potential.

Normalized energy PD and normalized remaining energy PD curve is similar, and they are both the monotone increasing function in range [−1,1]. We have also discovered when $\phi_e$ is too large (such as greater than 10), $U_e^{'}$ changes rather slowly, which makes sense, because distinguishing the neighbor with ED many times than the ED of local nodes is unnecessary, despite the fact that VPF-EBRP can do this when its other PD (such as the depth and the energy) is no different.

The weighted sum of the separate PF can be used to build one new VPF $V_m(i,t)$, which the PD $U_m(i,j,t)$ can be defined as follows:

$$U_m(i,j,t) = \alpha U_e^{'}(i,j,t) + \beta U_e(i,j,t) + (1-\alpha-\beta) U_d^{'}(i,j) \tag{7}$$

Here, $0 \leq \alpha \leq 1$, $0 \leq \beta \leq 1$, and $0 \leq \alpha + \beta \leq 1$. This mixed VPF will make data packets to transmit forward in the network of WMN. Weights $\alpha$ and $\beta$ decide the influence degree of PF of ED and RE for making the routing decisions.

### *3.3. Routing metrics*

Assume that WMN has $N$ nodes, the network topology is relatively stable for $i$, which could be any node (which may be the source node and the destination node or relay node), $N_i$ a collection of nodes within the transmission interference range of $i$ node. The node is equipped with a plurality of radio frequency (RF) devices. It can be transmitted or received data by different channels



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simultaneously. $R_i$ is the number of node $i$. $L_{(s,d)}$ is the link between the node $s$ and the node $d$. $C=\{1,2,3\ldots,c\}$ is the set of all orthogonal channels $O$ in the network.

(1) *Channel allocation*

On any link $l$ and any channel $c\in C$ allows the establishment of a multi-link communication between the two neighbors. These links work on different channels. At same time, maximizing network resource utilization and increase the data transfer rate between nodes of two neighbors.

Any channel allocation must meet the following constraints: RF constraints and interference constraints.

Radio frequency constraints is that at any time, a node can use a maximum of $R_i$ channels to send a data packet:

$$\sum_{s\in N}\sum_{i\,c=1}^{C} y_1^{ct} \le R_i, \forall \mathrm{d} \in \mathrm{N}, \mathrm{t} = 1,\ldots,T \tag{8}$$

Interference constraints is that at any time, two interference links cannot be active on the same channel.

$$\sum_{s'\in N_u'\cup N_u'}\sum_{d'\in N_u'} y_{l_{s',d'}}^{ct} \le 1, \forall\left(s', d'\right) \in \mathrm{L},\ c = 1,\ldots,C, t = 1,\ldots T \tag{9}$$

The number of link channels that is established by any node $i$ with its neighbors must be less than the number of RF. That is, there is channel allocation limit as follows.

$$\sum_{c=1}^{C} y_i^c \le R_i, i\in N \tag{10}$$

(2) *Rate allocation*

Let $v_l^c$ the data transfer rate of link $l$ on the channel $c$. In WMN, $v_l^c$ depends on the activation time of the link $l$. If $t_l^c = 0$, the node $S$ cannot transmit any data to the node on channel $c$, that is, $v_l^c = 0$. There is $v_l^c \le t_1^c \mathrm{v}_\mathrm{p}$, $v_p$, which means that the physical layer link bandwidth.

The link activation also disturbed restrictions, this section uses the protocols interference model of the communication range and interference range. The set of all nodes within the interference range of defined node $S$ is $IN(S)$. The link (s, d) set can be obtained mutual interference is

$$IL_{sd} = \{(m,n)|\forall m\in IN\ (s)\ \ or\ \ n\in IN\ \ (d)\} - \{(s,d)\} \tag{11}$$

We adopt CSMA access method based on the IEEE802.11, the link and its interference link cannot be activated at the same time, they need to share the link bandwidth of the physical layer. Therefore, there is a rate allocation restriction:

$$\frac{v_l^c}{v_p} + \frac{\sum_{l'\in IL_{sd}} v_{l'}^c}{v_p} \le 1, \forall l{\in}L, c{\in}C \tag{12}$$

$v_l^c/v_p$, which means the activation time of the link $l$ on the channel $c$.

(3) *Routing*

Due to the presence of interference in the system, conflict is inevitable. So once the conflict ensues, re-transmissions are needed to ensure the successful transmission in the system. Taking into account the link quality difference will affect the performance of WMN, we introduce the expected transmission count (ETX) routing metric. The value of link ETX is the forecast of data traffic using this link to contract. The calculation of ETX uses the forward and reverse transfer rate of link.

The collision probability is defined $p_l^c$ of $l$ link in the channel $c$, the expected transmissions number of successfully transmitted packets on this link is

 

$$ETX = m\left(p_l^c\right)^m + \sum_{k=1}^{m} k\left(p_l^c\right)^{k-1}\left(1 - p_l^c\right) \tag{13}$$

$m$ is the upper limit of re-transmission in the 802.11 standard. The time $t$ for the data packet size is $S_{\mathrm{p}}$, the link bandwidth is $B_{L(s,d)}$, the average transmission, which is needed by packets in link $l$, not only includes time of the transmission but also includes overhead of MAC and physical layer. Taking into account the overhead of channel on the MAC layer and the physical layer, the average transmission time of packet for the channel on the link is

$$t_l^c = t_l^{c,overheads} + \frac{S_P}{B_l} \tag{14}$$

re-transmission expectations flow on channel $c$ is

$$T_l^c = r_l^c \times ETX \tag{15}$$

The former is the average flow rate. By the aforementioned formula, using the expected transmission time (ETT) value of $c$ channel on the link $l$ is

$$ETT_l^c = \frac{T_l^c}{r_1^c} \times t_l^c \tag{16}$$

So the total value of ETT in the same path and the same channel $c$ is

$$\sum_{l \in L} ETT_l^c = \sum_{l \in L} \left(T_l^c / r_l^c\right) \times t_l^c \tag{17}$$

### 3.4. *Design of VPF-EBRP*

The details of the design and achievement of VPF-EBRP are shown as follows.

Its payload of the routing message for control in VPF-EBRP consists of two additional parts: 'depth' and 'energy'. VPF-EBRP designs two types of messages for control. The first one is a common update message, its field type can be marked as 00, the other fields of VPF-EBRP include information to be used, such as depth and energy. The distance of two neighbors may be obtained through a variety of techniques, such as assessments or estimates of the signal attenuation based on the received signal strength indicator. Notably, the distance adopted in VPF-EBRP can be approximation, because it can be distinguished whether it is far away from local nodes or not. If a sensor node of WMN receives some update messages from its neighbor nodes, it needs to update the routing table and re-select one next-hop node by the method.

(1) *Depth*

By default, the depth of all sensor nodes in WMN is set to 0 at beginning, in addition to the sink node, which the initialized depth is 0. The sink node sends update messages first, the sensor nodes of WMN with one-hop away from the sink node can obtain their own depth by increasing number 1 to its depth value in relative changed message among WMN. After that is carried out, by receiving the sent update message from its neighbor nodes of WMN, other nodes also get their own depth, and their neighbors have the depth value in a similar way of one-hop node. The step of main algorithm for VPF-EBRP shows the pseudo code.

(2) *Energy*

As we know, VPF-EBRP should know the RE on the nearby local nodes of WMN. It should be supported by the popular hardware platforms of WMN. In particular, a pure software method can be used for this. The all operations performed by local nodes can be recorded, and the appropriate battery model can be used to estimate the energy consumption. In this process, the RE value will be obtained based on strategies mentioned earlier. The RE value should be

 
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transmitted when updating messages, so that each node of WMN can know the RE of all their neighbor nodes and record their value in the relative routing table. The density of energy of sensor node in local position will be obtained by calculating the whole RE of neighbor nodes in the relative routing table, and then this RE sum of neighbor nodes divided by the region of radio coverage area.

VPF-EBRP uses parameter named maximum update interval (MUI) and parameter named minimum update interval (LUI) between two successive update messages. If the experienced time is more than MUI, if the depth or energy has to be changed, the node will immediately transmit one new update message. The relatively updated messages will be sent between the LUI and MUI. If none of the updated messages come from the neighbor node at about two time intervals, the relative neighbor node should be considered to be killed, then VPF-EBRP needs to calculate the depth and other values again. When any one of the following events occur, VPF-EBRP should send one relative update message. If the energy of a node has been consumed, 5% of the RE is sent in a previous update message, and the time since the previous update message is larger than any LUI, the node needs to transmit one updated message to other nodes. At the same time, if the node depth has changed, and the time since the previous update message is larger than any a LUI, the node needs to transmit one updated message to other nodes.

In order to describe the step of main algorithm for VPF-EBRP, we define the following as a set of functions.

The function of *scanRoutingTable*() scans the routing information of the works in WMN; the *setChannel*() selects one channel to the transmission; the *calculateEnergy*() computes and sends back the value of ED of local nodes; the *calculateLocalDepth*() calculates local depth (*LD*) of the transmission path; the s*electLowestDepth*() selects the Lowest Depth from the routing table; the *setLocalDepth*() sets up value of the depth of local nodes; the *selectParentNode*() selects the parent node according to the rule of max-$U_m$, max-$U_{ed}$, max-$U_e$, min-u_Msg.DEPTH, min-COST, and so on; the *setRate*() allocates the rate to the transmission; the *calculateRouting*() calculate the parameters *ETX* and *ETT* of the path based on Equation (13); the *updateRoutingTable*() updates the routing table; the *Transmit*() sends the data along the selected path.

The Step of main algorithm for VPF-EBRP is as follows (which is the pseudo code).

1: Set flag *f* is function value of *canRoutingTable* //Flag *f* = *scanRoutingTable*()
2: Set integer *c* is function value of *setChannel* //*c* = *setChannel*()
3: Set real *LE* is function value of *calculateLocalEnergy* //*LE* = *calculateLocalEnergy*()
4: Set real *LD* is function value of *calculateLocalDepth* //*LD* = *calculateLocalDepth*()
5: $\phi_d = (LD+1)/(\mathrm{u\_Msg.\,Depth}+1)$
6: If $\phi_d > 1$ & eq. ((10)) is T then $U_d = 1 - 1/\phi_d$ else $U_d = \phi_d - 1$ // $U_d = \phi_d > 1$ & eq. (10) is T? $1 - 1/\phi_d : \phi_d - 1$
7: $\phi_e = \mathrm{u\_Msg.\,Energy}/LE$
8: If $\phi_e > 1$ & eq. ((12)) is T then $U_e = 1 - 1/\phi_e$ else $U_e = \phi_e - 1$ // $U_e = \phi_e > 1$ & eq. (12) is T? $1 - 1/\phi_e : \phi_e - 1$
9: $\phi_e^{'} = \mathrm{u_M sg.Energy}/LE$
10: If $\phi_e^{'} > 1$ & eq. ((12)) is T then $U_e^{'} = 1 - 1/\phi_e^{'}$ else $U_e^{'} = \phi_e^{'} - 1$ // $U_e^{'} = \phi_e^{'} > 1$ & eq. (12) is T? $1 - 1/\phi_e^{'} : \phi_e^{'} - 1$
11: $U_m = (1 - \alpha - \beta)\cdot U_d + \alpha\cdot U_e^{'} + \beta\cdot U_e$
12: Set flag *g* is *updateRoutingTable* function value //Flag *g* = *updateRoutingTable*(neighbor_ID)
13: Set parameter *LD* is function value of *selectLowestDepth* //*LD* = *selectLowestDepth*()
14: Set flag *h* is function value of s*etLocalDepth with LD* //Flag *h* = s*etLocalDepth*(LD)
15: Set flag *p* is function value of *selectParentNode* //Flag *p* = *selectParentNode*()
16: Call function *setRate* //*setRate*()
17: Call function *calculateRouting* //*calculateRouting*()
18: Call function *updateRoutingTable* //*updateRoutingTable*()
19: Call function *Transmit* //*Transmit*()
20: Return to step (1) //goto (1)



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## 4. SIMULATION EXPERIMENT

We analyze the performance of VPF-EBRP algorithm by simulation experiments, which are conducted on TOSSIM platform, NS2, and MATLAB. As mentioned earlier, there are already a lot of work balancing energy consumption through a variety of ways, such as optimization deployment of sensor nodes of WMN, topology reconstructing and node aggregation. As far as we know, almost no work focused on developing a balanced energy consumption routing protocols, most energy-aware routing program will focus on the energy efficiency. Mint_Route strategy [18] is designed to achieve high reliability by choosing the best qualified path, which is mainly measured by the delivery ratio of packets. Although some literatures provide the simulation and experimental results of performance evaluation, as far as the authors know, there is no previous research works to mention impact on performance by deployment strategies, effect of failure, and the density of nodes for WMN. We select Mint_Route, which is a standard routing algorithms of energy efficiency, as well as LEACH, a typical hierarchical routing strategy, as reference protocol.

### *4.1. Performance factors*

In order to get assessment of the method, we give the following definitions of performance indicators.

(a) Energy balance factor (EBF). The EBF can be used to calculate the energy-balanced features of routing approach. It is regarded as basic deviation of the RE of the sensor nodes in WMN:

$$EBF = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[E_i(t) - E_{avg}(t)\right]^2} \tag{18}$$

$N$ is the number of the whole network nodes, $E_i(t)$ is the RE of node $i$ at time $t$, $E_{avg}(t)$ is the average value of the RE of all the nodes.

(b) First death sampling node (FDSN). The effective working time of the certain transaction is regarded as the duration of the transaction being executed totally. In our simulations, the effective working time is regarded as time interval between starting of the transaction and the FDSN appears. As we know, the lifetime of WMN can be decided by the network segmentation and network coverage.

(c) Effective working throughput (FT). Effective working throughput can be regarded as the number of data packets, which are received by the sink node in effective working time.

(d) Packets lifetime of node (PLN). We set the coordinate of data as random, and average packets emerging rate is given to test the performance of each protocol. The PLN can be used as an indicator to assess effect of energy occupation for its performance evaluation. Furthermore, it can be noted that if the sink node can get data packets from the sensor source node, then the energy hole can be ignored, network connectivity can be better. Data reception rate can be used as the rate between the real ratio of the sink node's receiving data packets and the desired receiving rate. The PLN can be used to calculate the earnings of energy balancing use or consumption.

(e) Normalized transmission overhead (NTO). NTO can be used as analyzing the complexity of the proposed strategy and the additional cost of VPF-EBRP. The complexity degree metrics of the proposed strategy includes context gathering overhead ($O_{\mathrm{cg}}$) of WMN, energy fusion analysis overhead ($O_{\mathrm{efa}}$) of WMN, transmission overhead ($O_{\mathrm{t}}$) of data packet among nodes of WMN, and so on. According to classical complexity analysis method of algorithm [1], from formula (7), ((12)), ((17)), and so on, we can know that the complexity degree of the proposed strategy belongs to O($n$). The additional cost metrics of VPF-EBRP includes calculating cost of depth and energy ($C_{\mathrm{de}}$) of VPF. NTO of each group in WMN can be calculated from above overhead and cost as the following formula (19).



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$$NTO = \sum_{i=1}^{MC}\sum_{j=1}^{MC}\left(\xi O^{cg}_{(i,j)} + \psi O^{efa}_{(i,j)} + \zeta O^{t}_{(i,j)} + (1-\xi-\psi-\zeta)C^{de}_{(i,j)}\right) \tag{19}$$

*MC* is the node size number of the each group in WMN, such as MC = 60, which means there is 60 nodes in a certain group of WMN. Integer parameter $i$ and $j$ are node index of the each group in WMN.Parameter $\xi$, $\psi$, $\zeta$ are weight real value, $\xi$, $\psi$, $\zeta \in [0, 1]$ and $\xi+\psi+\zeta \prec 1$, such as default real value $\xi=0.25, \psi=0.25, \zeta=0.25$. $O^{cg}_{(i,j)}, O^{efa}_{(i,j)}, O^{t}_{(i,j)}, C^{de}_{(i,j)}$ are normalized real value of overhead of node $i$ and $j$ of each group in WMN.

### 4.2. Simulation parameters and scenarios

We use a 19 × 19 grid network (total 361 nodes, each one is at the intersection of the 19 row and the 19 column) to carry out simulation experiments to assess the performance of program VPF-EBRP, and compare it with algorithm and protocol LEACH. In this particular topology, one node of WMN can communicate with its eight direct different neighbors. According to a certain order, the node can often play a role in sampled nodes or relay nodes. One scenario is as Figure 3. Parameters for simulations are shown in the Table I. The similar experiment will be carried out 12 times or more, the average value of the performance indicators and the standard deviation of simulation is computed based on the formula mentioned earlier.

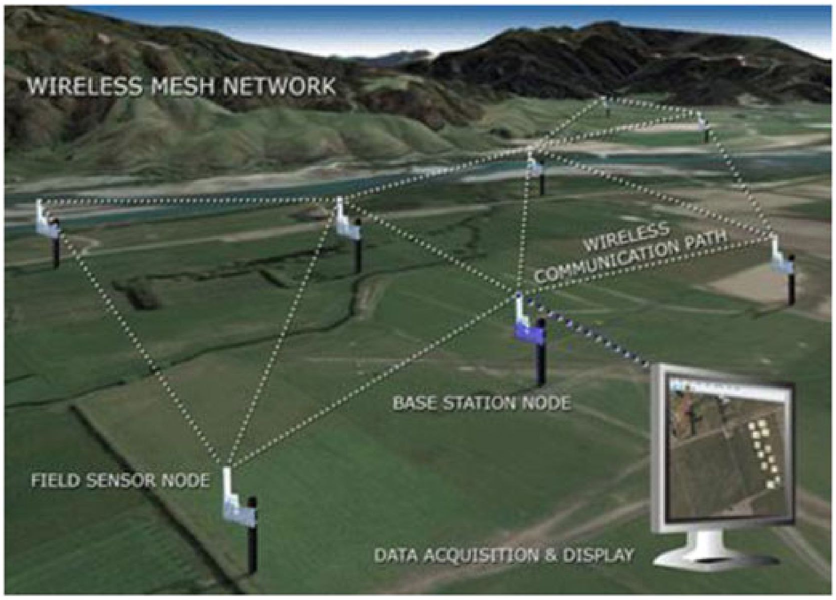


Figure 3. One scenario of wireless mesh network.

Table I. Parameter configuration for simulations.

| | | |
|---|---|---|
| Deploy of parameters | Deployment area | 100 m × 100 m rectangle |
| | Deployment type | 19 × 19 grid |
| | Network structure | Isomorphism, plane |
| | The number of nodes | 361 |
| | The sink node | (50, 50)m |
| | node | Total energy 12 000, radio range 7 m |
| VPF-EBRP | $(\alpha, \beta)$ | (0.25, 0.25) |
| | MUI | 12 s |
| | LUI | 6 s |
| Simulation time | Time | 9000 s |

MUI, maximum update interval; LUI, minimum update interval.



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### 4.3. The simulation results

Mint_Route always choose the shortest path, so it often soon runs out of the energy of node on this place. The size of each cluster are random, there is no consideration of the energy hole, the energy consumption rate of the portion of the nodes close to the sink node, and the rotation of cluster head does not consider the energy. However, once VPF-EBRP finds that the value of ED in some areas is smaller than others of the area around, it will choose other paths with areas of more energy. So VPF-EBRP can make the balance of overall network energy consumption improved and prolong the lifetime of network and effective working time. The statistical relative results by us are shown in Table II. The calculation result of EBF decreased by 22.8%, whereas VPF-EBRP respectively prolonged the time of FDSN by 78.3%. The effective working throughput is improved as well. The statistic results listed in Table II indicate the increase of 110.3%, as VPF-EBRP maintained relative higher PLN than Mint_Route and larger FDSN. For EBF, the smaller standard deviation of several relative performance indicators shows that VPF-EBRP has higher robustness to the interference of all noises, and it also can keep the stable performance.

Figure 4 shows the ratio comparison of surviving node among three strategies. We can know the function of ratio of surviving nodes change over time in the simulations. These times in which the first death node occurs in VPF-EBRP is later than which in Mint_Route. In addition, the PLN of VPF-EBRP is much higher than PLN of Mint_Route. From the simulation results by the experiments, we can draw the conclusion that these gains can be obtained by energy consumption balance of VPF-EBRP, the correctness and integrity of these data that is received by VPF-EBRP is much better than which in Mint_Route, because there are less losses of packet in VPF-EBRP.

Figure 5 shows comparison of EBF among three strategies based on the above mentioned formula (18), which is the EBF of three strategies in 350 rounds experiments [12]. In Figure 5, the EBF of VPF-EBRP increases slightly at first, and keep a stable situation before Round 250, then increase a little time and return to 0 as the energy of the whole network is using up. EBCMAC is from reference [3], because it only focused on a level of media access control, other levels were not considered, the deviation of the RE of the sensor nodes in WMN is more than SFEB from reference [2] and VPF-EBRP in this paper.

Table II. Statistical data of performance indicators.

| | Mint_Route | | LEACH | | VPF-EBRP | |
|---|---|---|---|---|---|---|
| Project | Average | Standard deviation | Average | Standard deviation | Average | Standard deviation |
| EBF | 192.3 | 3.21 | 171.6 | 10.98 | 152.4 | 7.96 |
| FDSN(s) | 4772.5 | 229.1 | 6808.3 | 65.2 | 7811.6 | 34.6 |
| FT(pkts) | 7855.2 | 554.9 | 12923.1 | 0.12 | 17612.0 | 0.25 |

LEACH, low energy adaptive clustering hierarchy; EBRP, energy-balanced routing protocol; EBF, energy balance factor; FDSN, First death sampling node.

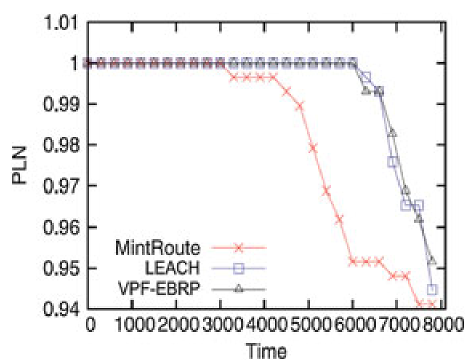


Figure 4. The ratio comparison of surviving node among three strategies.

 

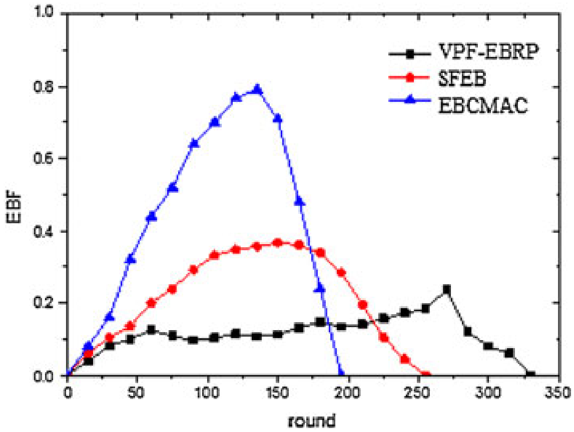


Figure 5. Comparison of energy balance factor among three strategies.

Figure 6 shows comparison of NTO among four strategies based on the aforementioned formula (19). In Figure 6, case (a) is VPF-EBRP in this paper, case (b) is EBCL from reference [4], case (c) is EBCMAC from reference [3], and case (d) is SFEB from reference [2]. The advantage of NTO of VPF-EBRP in this paper is obvious. NTO of EBCL from reference [4] is close to VPF-EBRP in this paper in certain MC group size. NTO of SFEB from reference [2] is more than other strategies because its two-phase aggregation process and the dynamic aggregating selection mechanism must use more overhead.

We have conducted extensive simulation and experiments to study the performance of the proposed strategy in this paper compared with existing protocols. From the relative results, we can see that VPF-EBRP has a higher performance than Mint_Route, LEACH, EBCL, EBCMAC, and SFEB, which balances the energy consumption, prolongs the function lifetime and guarantees high QoS (such as energy-balanced, long-surviving) of WMN.

It can be found that VPF-EBRP costs a little when it changes to one alternative path. Furthermore, it is very meaningful that VPF-EBRP changes the routing in many areas and flow the data packets by multiple selected paths. It shows that VPF-EBRP may relieve congestion case in the shortest and limited energy occupation caused by losing data packets. Our strategy takes advantage of multipath routing in the source node to report collected data, and this may save computing and sensor storage resources. In a number of sources—the case of aggregation nodes can share the adaptive node, so that they rest of the rational use of existing energy. Simulation results demonstrate that our strategy effectively improves the routing energy efficiency.

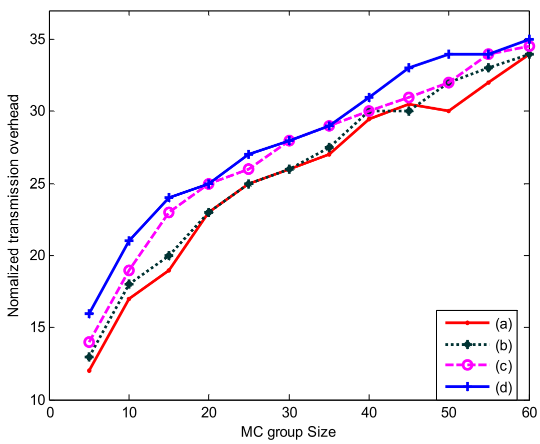


Figure 6. Normalized transmission overhead comparison among strategies: (a) VPF-EBRP; (b) EBCL; (c) EBCMAC; (d) SFEB.

## 5. CONCLUSION AND FUTURE WORKS

Wireless mesh network consists of numerous wireless sensors, the energy and communication ability of which are limited. A kind of novel VPF-based energy-balanced routing strategy for WMN has been presented in this paper. The energy-balanced routing strategy can establish a virtual integrated PF by drawing on classical potential concept of physics, driving data packets through dense energy area forward the sink node and bypass the nodes with low RE so as to protect the nodes with relatively low energy. The energy can be consumed as uniformly as possible in the such similar deployment of scenarios of WMN. By comparing with the other energy-efficient routing strategy from our selected scenarios, the results of simulation and experiments show that energy balance and throughput can be improved. In the near future, we will do more research analysis works on the complexity of the proposed approach and the additional cost of VPF-EBRP.

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