Green Communication in Energy Renewable Wireless Mesh Networks: Routing, Rate Control, and Power Allocation

Changqing Luo, Shengyong Guo, Song Guo, Laurence T. Yang, and Geyong Min

Abstract—The increasing demand for wireless services has led to a severe energy consumption problem with the rising of greenhouse gas emission. While the renewable energy can somehow alleviate this problem, the routing, flow rate, and power still have to be well investigated with the objective of minimizing energy consumption in multi-hop wireless mesh networks (WMNs). This paper formulates the problem of network-wide energy consumption minimization under the network throughput constraint as a mixed-integer nonlinear program by jointly optimizing routing, rate control, and power allocation. Moreover, the min-max fairness model is applied to address the fairness problem because the uneven routing problem may incur the sharp reduction of network performance in multi-hop WMNs with renewable energy. Due to the high computational complexity of the formulated mathematical programming problem, an energy-aware multi-path routing algorithm (EARA) is also proposed to deal with the joint control of routing, flow rate, and power allocation in practical multi-hop WMNs. To search the optimal routing , it applies a weighted Dijkstra's shortest path algorithm, where the weight is defined as a function of the power consumption and residual energy of a node. Extensive simulation results are presented to show the performance of the proposed schemes and the effects of energy replennishment rate and network throughput on the network lifetime.

Index Terms—Multi-hop wireless mesh networks, renewable energy, fairness, energy consumption minimization, routing.

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1 INTRODUCTION

The increasing demand for ubiquitous network access leads to the rapid development of wireless access networks. The multi-hop wireless mesh network (WMN), as a promising solution for low-cost broadband Internet access, is being used on the last mile for enhancing Internet connectivity for mobile users. A multi-hop WMN is usually constructed by wireless mesh nodes that are wireless mesh routers or gateways. The nodes are rarely mobile, and do not have power constraints. A high volume of traffic can be effectively delivered on wireless channels via multi-hop wireless paths.

In the past years, researchers largely concentrate on the channel assignment, routing, and rate allocation problems in multi-hop WMNs [1], [2], [3]. Subramanian *et al.* [4] investigated the channel assignment problems in multi-radio WMNs, and designed centralized and distributed algorithms for the channel allocation with the objective of minimizing the overall network interference. Capone *et al.* [5] addressed the radio resource assignment optimization problem in WMNs where routing, scheduling and channel assignment were jointly considered. Passos and Albuquerque [6] considered the routing and rate adaptation problem in WMNs, and proposed a joint automatic rate selection and routing scheme to provide best routing and rate. Besides, since energy consumption is becoming a very important problem in the world for the rising of greenhouse gas emission, energy efficiency has been attracting much attention [7], [8]. Vijayalayan *et al.* [9] considered the energy efficient scheduling scheme in WMNs and an enhanced pseudo random access scheme was proposed to improve the energy efficiency. The power control problem in WMNs was also investigated to reduce the interference and energy consumption [10], [11], [12]. However, although some work have been done to reduce energy consumption, the effect is essentially marginal.

On the other hand, the power grid infrastucture, which provides electricity to multi-hop WMNs, has been experiencing a dramatic change from the tranditional electricity grid to the smart grid where renewable energy is integrated [13], [14]. Renewable energy is usually extracted from renewable resources (e.g., solar and wind) so that no fossil fuel is burn and thus no greenhouse gas is produced. Therefore, the use of renewable energy, to some extent, can alleviate the greenhouse gas emission problem.

However, the routing, flow rate, and power allocation problem still has to be well investigated in multi-hop WMNs with renewable energy because renewable energy replenishment of each node in multi-hop WMNs is highly dependent on the environment. The energy replenishment rate dynamically changes over time, and is affected by the weather and surrounding environment. Hence, new problems are posed in multi-hop WMNs with renewable energy. In recent years, a few research

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efforts have been made to investigate the problems in multi-hop WMNs with renewable energy. Badawy, Sayegh, and Todd [15] investigated the resource assignment problem so as to minimize the network deployment cost. Cai *et al.* [16] investigated the resource management problem in sustainable energy powered WMNs and an adaptive resource management scheme is proposed to distribute traffic under the energy sustainability constraint. In particular, a G/G/1 queue is applied to model the energy buffer of a mesh node and a diffusion approximation is then used to analyze the transient evolution of the queue length. Zheng *et al.* [17] proposed an energy-aware AP placement scheme in WLAN mesh networks with renewable energy where the optimal placement of APs is determined and the power constrol and rate adaptation at APs are jointly considered. Lin, Shroff, and Srikant [18] investigated the routing problem for multi-hop WMNs with renewable energy, and proposed an asymptotically optimal energy-aware routing scheme in which energy replenishment, mobility, and erroneous routing information were jointly considered.

However, the work on joint control of routing, rate, and power to minimize network-wide energy consumption under network throughput constraint in multi-hop WMNs with renewable energy is still missing in the current literature. In fact, routing, rate control, and power allocation are highly interdependent, and have significant influence on the energy consumption in multi-hop WMNs. Therefore, they should be simultaneously considered to minimize the network-wide energy consumption.

To this end, this paper proposes a scheme jointly considers the routing, rate control, and power allocation tominize network-wide energy consumption with network throughput constraint in multi-hop WMNs. The key contributions of this paper are summarized as follows.

1) The network-wide energy consumption minimization under the network throughput constraint in multi-hop WMNs with renewable energy is investigated and a scheme that jointly considers the routing, flow rate, and power allocation is proposed to deal with this problem. Moreover, the network-wide energy consumption minimization problem is formulated as a mixed-integer nonlinear program (MINLP) that is in general NP-hard.
2) Fairness is also taken into account in the proposed scheme to address the uneven routing problem which may lead to some severe performance issues (e.g., some nodes frequently enter the sleep mode for the residual energy of these nodes is below a threshold.) in multi-hop WMNs with renewable energy compared to traditional multi-hop WMNs. The min-max fairness model is applied to address the fairness problem, which can achieve the trade-off between the power consumption and residual energy of a node in multi-hop WMNs with renewable energy.
3) An energy-aware multi-path routing algorithm (EARA) is proposed to deal with the joint control of routing, rate control, and power allocation in practical multi-hop WMNs where the solution to MINLP problem has high computation complexity. This algorithm uses a weighted Dijkstra shortest path algorithm to search an optimal routing and the weight is defined as a function of the power consumption and residual energy of a node. Moreover, the concept of unit flow that consists of a session flow is proposed to address the issue that the weighted Dijkstra shortest path algorithm can not support multi-path routing.

The remainder of this paper is organized as follows. Section 2 describes the network model, including the considered network scenario, session flow model, and power and energy consumption model. The network-wide energy consumption under network throughput constraint is formulated as a MINLP problem and the fairness is also consider to address the uneven routing problem in Section 3. Section 4 proposes an energy-aware routing algorithm that can be used in practical multi-hop WMNs. Extensive simulation results are presented and analysed for performance evalution in Section 5. Finally, Section 6 concludes this paper.

2 NETWORK MODEL

This paper considers a multi-hop WMN with renewable energy, represented by a directed graph $\mathcal{G} = \{\mathcal{N}, \mathcal{L}\}$, where $\mathcal{N}$ and $\mathcal{L}$ are the sets of nodes and directional links, respectively. A link between two nodes exists if and only if the two are within the a certain communication range. The communication between two node without a direct link needs to resort to multi-hop communication with the help of intermediate nodes' relaying. Orthogonal channels are used by all links so that the interference can be avoided. It is noteworthy that the number of channels is as many as the number of active links because a channel can be reused spatially. The multi-hop WMN is considered to work as a time-division system in which the time is divided into slots with equal length T and t refers to the t-th discrete time period. We assume that no new session occurs during a time slot; thus, the existing session flow will not be changed.

In particular, each node is considered to be powered only by renewable energy for aiming to investigate effects of renewable energy on the joint control of routing, rate, and power allocation with the objective of minimizing the network-wide energy consumption in multi-hop WMNs. The solar is the renewable energy source and a large-size solar panel is deployed for a node. The structure of a node is shown in Fig. 1 where solar energy is transformed into electrical energy through a solar panel. The electrical energy will be stored into the battery via a charging controller, and then used to

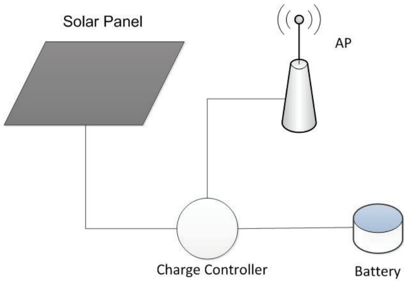

Fig. 1. The node structure supplied with renewable energy.

power the access point (AP). Once the energy contained in the battery is lower than a threshold, the charging controller will immediately shut down the power supply so that the node enters the sleep mode. Due to the low energy production rate, the energy replenishment rate of a node is assumed to be less than the energy consumption rate when a session is delivered through the node. When a node works, its residual energy will gradually reduce till it reaches the predefined threshold B_{outage}. As long as the residual energy of a node is greater than B_{outage} after replenishing energy, the node will be activated. Moreover, when the residual energy reaches the maximum capacity of a battery B_{max}, the energy replenishment will stop. In other words, the residual energy of a node varies between B_{outage} and B_{max}.

2.1 Session Flow Model

There is a set of $\mathcal{F}$ active session flows in the network. It is noteworthy that the unicast communication session is considered. Let $s(f)$ and $d(f)$ denote the source and destination nodes of a session flow $f \in \mathcal{F}$, respectively. Moreover, $r(f)$ represents the data rate of session flow f. Therefore, for the network with $|\mathcal{F}|$ active session flows, network throughput U is the sum of data rate of all session flows, i.e.,

$$U = \sum_{f \in \mathcal{F}} r(f). \tag{1}$$

To achieve data transmission between a source node and its corresponding destination node, the multi-path flow routing scheme is applied in this study. Hence, each session flow can be splitted, and delivered through multiple paths. Let $r_l(f)$ denote the amount of flow rate on link l that is attributed to session flow $f \in \mathcal{F}$. $\mathcal{L}_i^{In}$ and $\mathcal{L}_i^{Out}$ represent the set of potential incoming links and the set of potential outgoing links at node i, respectively. Since session flow needs to satisfy rate balance, the following equations can then be obtained. If node i is the source node of session f, i.e., $i = s(f)$, then

$$\sum_{l \in \mathcal{L}_i^{Out}} r_l(f) = r(f). \tag{2}$$

If node i is the destination node of session f, i.e., $i = d(f)$, then

$$\sum_{l \in \mathcal{L}_i^{In}} r_l(f) = r(f). \tag{3}$$

If node i is an intermediate node of session f, i.e., $i \neq s(f)$ and $i \neq d(f)$, then

$$\sum_{l \in \mathcal{L}_i^{Out}}^{l \neq (i, s(f))} r_l(f) = \sum_{l' \in \mathcal{L}_i^{In}}^{l' \neq (d(f), i)} r_{l'}(f). \tag{4}$$

Since the quality of service (QoS) for each users needs to be guaranteed in multi-hop WMNs, the data rate of each session flow should be met when the joint control scheme of routing, rate, and power is designed.

2.2 Power and Energy Consumption Model

In general, when a session is delivered on a link in multi-hop WMNs with renewable energy, the energy is mainly consumed due to data transmission and reception. The receiving power is denoted by P_{rec}, which is assumed to be a constant. The transmission power is represented by P_l when link l is active. It is obvious that transmission power is a variable parameter that is related to the quality of the link and the rate allocation.

X_l is denoted as a binary variable indicating whether or not link l is active, i.e.,

$$X_l = \begin{cases} 1, & \text{if link } l \text{ is active, } l \in \mathcal{L}, \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

Hence, the energy consumption for link l is $(P_l + X_l \cdot P_{rec})$.

The maximum transmission power for each node is defined as P_{max}. Since transmission power can not exceed the maximum transmission power, the following relationship can be obtained

$$0 \leq P_l \leq X_l \cdot P_{max}, l \in \mathcal{L}. \tag{6}$$

Since there may be a number of outgoing links at node i, the transmission power constraint can be expressed as follows

$$0 \leq \sum_{l \in \mathcal{L}_i^{Out}} P_l \leq P_{max}, l \in \mathcal{L}, i \in \mathcal{N}. \tag{7}$$

Let E_i denote the total energy consumption at node i during a time slot, which can be expressed as

$$E_i = (\sum_{l \in \mathcal{L}_i^{Out}} P_l + \sum_{l \in \mathcal{L}_i^{In}} X_l \cdot P_{rec}) \cdot T, l \in \mathcal{L}, i \in \mathcal{N}. \tag{8}$$

In multi-hop WMNs with renewable energy, renewable energy will be supplied to each node except that its battery is full. Denote $B_i(t)$ as the residual energy of node i at the beginning of time slot t and $R_i(t)$ represents as the replenished energy of node i during time slot t. It is a common sense that $R_i(t)$ is highly related to geographical location, environment, climate and other natural factors. After a time slot, the residual energy of node i is

$$B_i(t+1) = \min\{B_{max}, \max[B_{outage}, B_i(t)+R_i(t)-E_i(t)]\}, \tag{9}$$

where $R_i(t) = r_i(t) \cdot T$, and $r_i(t)$ is the energy replenishment rate. The energy for each node in multi-hop WMNs with renewable energy is updated through (9).

For link l, the link capacity can be obtained through Shannon formula

$$c_l = W_l \log_2(1 + \frac{P_l G_l}{\sigma^2}), l \in \mathcal{L}, \tag{10}$$

where c_l, W_l, and G_l are the achievable capacity, bandwidth, and channel gain of link l, respectively; σ^2 is the ambient Gaussian noise power. Accordingly, when maximum transmission power is used, the corresponding maximum capacity c_l^{max} is

$$c_l^{max} = W_l \log_2(1 + \frac{P_{max} G_l}{\sigma^2}), l \in \mathcal{L}. \tag{11}$$

Since session flow rate on any link cannot exceed the link's capacity, we have

$$\sum_{f\in\mathcal{F}} r_l(f) \le c_l, l \in \mathcal{L}, . \tag{12}$$

Through combining (10) and (12), the following relationship can be obtained

$$\sum_{f\in\mathcal{F}} r_l(f) \le W_l \log_2(1 + \frac{P_l G_l}{\sigma^2}), l \in \mathcal{L}, . \tag{13}$$

3 PROBLEM FORMULATION

The section studies how to jointly control the routing, rate, and power so as to achieve the network-wide energy consumption minimization under the network throughput constraint in multi-hop WMNs with renewable energy. This problem is motivated by the scenario where users have strict network throughput limit. Hence, given the network throughput constraint, the optimization problem is to minimize network-wide energy consumption by jointly controlling the multi-path routing, rate for each session flow, and power on each link.

Mathematically, this problem can be formulated as follows:

$$\begin{aligned} \textbf{OPT:} \quad & \textbf{min} \quad \Sigma_{i\in\mathcal{N}} E_i \\ & \textbf{s.t.} \quad (1)-(4), (6)-(8), \text{ and } (13) \\ & \qquad x_l \in \{0,1\}, P_l, r_l(f) \ge 0. \end{aligned}$$

OPT is a mixed-integer nonlinear program (MINLP), which is in general NP-hard [19]. It seeks a feasible routing vector for a session flow in $f \in \mathcal{F}$ along with the corresponding rate vector on each link $l \in \mathcal{L}$ and power vector for each node $i \in \mathcal{N}$ such that the network-wide energy consumption of the triples vector (i.e., routing, rate, and power) is minimum among all feasible vectors. Based on the results of solving this formulation, the optimal routing, rate control, and power allocation can be obtained.

However, simply minimizing the network-wide energy consumption can lead to a severe bias that some wireless mesh nodes are starved and some other nodes are satiated. That is, some nodes may be always selected to deliver session flows due to its high-quality outgoing or incoming links while some other nodes may have no opportunity to deliver session flows. It is well known that this phenomenon will result in some severe performance problems in multi-hop WMNs, such as unbalanced traffic load and network acess collision [20], [21]. This problem may be more severe in multi-hop WMNs with renewable energy compared with traditional multi-hop WMNs since the energy at each node is limited and supplied through energy replenishing from solar. Because some nodes may frequently enter the sleep mode for their residual energy is less than the threshold. Therefore, fairness should be considered when the scheme of jointly controlling routing, rate, and power is designed in multi-hop WMNs with renewable energy.

This paper addresses the fairness issue based on a simple min-max fairness model, which leads to minimum network-wide energy consumption with guaranteed minimum maximum power allocation of each node according to its residual energy. The goal of achieving fairness is that the lower energy is consumed by a node with lower residual energy while the higher energy is consumed by a node with higher residual energy. Therefore, min-max fairness is used to limit the transmission power of each node as a value. By letting

$$\alpha = \max_{i\in\mathcal{N}} \{\alpha_i\}, \text{ and}$$

$$\alpha_i = \frac{P_i / \sum_{i\in\mathcal{N}} P_i}{B_i / \sum_{i\in\mathcal{N}} B_i}$$

denote the fairness constraint factor, we then have

$$P_i \le \frac{B_i}{\sum_{i\in\mathcal{N}} B_i} \cdot \sum_{i\in\mathcal{N}} P_i \cdot \alpha, i \in \mathcal{N}, l \in \mathcal{L}, \tag{14}$$

where $P_i = \sum_{l\in\mathcal{L}_i^{Out}} P_l$ is the transmission power of node i.

Through (14), the transmission power of each node is constrained so that the network-wide residual energy is balanced. It can be shown that the maximum allowed transmission power is proportional to the residual energy of the node. Fair constraint factor α can be derived through solving **MIN-MAX**, and then is used for solving **OPT-F** to obtain routing and power allocation.

$$\begin{aligned} \textbf{MIN-MAX} \quad & \textbf{min} \quad \alpha \\ & \textbf{s.t.} \quad (1)-(4), (6)-(8), (13), \text{ and } (14) \\ & \qquad x_l \in \{0,1\}, P_l, r_l(f) \ge 0. \end{aligned}$$

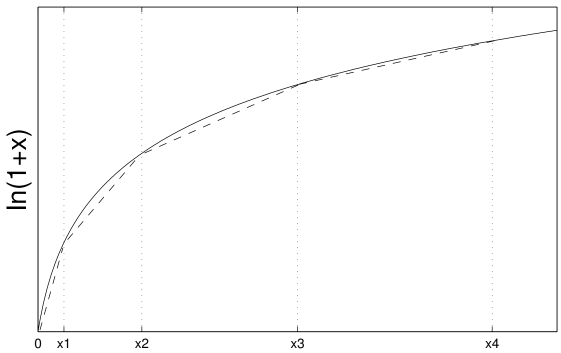

Fig. 2. An illustration of piece-wise linear approximation.

$$\begin{aligned} \textbf{OPT-F:} \quad & \min \quad \Sigma_{i \in \mathcal{N}} E_i \\ & \textbf{s.t.} \quad (1)-(4), (6)-(8), (13), \text{ and } (14) \\ & \qquad x_l \in \{0, 1\}, P_l, r_l(f) \geq 0. \end{aligned}$$

The result of solving **MIN-MAX** is consistent with that of solving **OPT** when all nodes have same residual energy. Compared with **OPT**, the objective of **OPT-F** is to minimize the network-wide energy consumption while making sure that each node i has a minimum power allocation among all maximum allowed power. Therefore, solving **MIN-MAX** firstly to obtain α and then solving **OPT-F** can provide a min-max guaranteed power and corresponding routing and rate.

It is obvious that **MIN-MAX** and **OPT-F** are also MINLP. So far, some techniques have been proposed to address general MINLP problems, e.g., branch-and-bound [22], outer approximation method [23]. However, these can only handle small-size problems. In addition, as shown in **OPT**, **MIN-MAX**, and **OPT-F**, only (13) involving log function is a nonlinear equation. This log function can be approximately transformed into a series of piece-wise linear functions [24]. It is a common sense that solving a mixed-integer linear programming (MILP) problem is much easier than solving a MINLP problem.

The idea of the piece-wise linear approximation is to use a series of linear functions to approximate the log function and replace it as shown in Fig. 2. Eq. (13) can be written as

$$c_l = \frac{W_l}{\ln 2} \ln(1 + \frac{P_l G_l}{\sigma^2}), l \in \mathcal{L}. \tag{15}$$

For simplicity of the presentation, $x_l = \frac{P_l G_l}{\sigma^2}$, and then the following equation can be obtained

$$c_l = \frac{W_l}{\ln 2} \ln(1 + x_l), l \in \mathcal{L}. \tag{16}$$

Variable x_l is the range $[0, x_l^{max}]$ evenly divided into several segments, where

$$x_l^{max} = \frac{P_{max} G_l}{\sigma^2}.$$

According to the result in [24], the piece-wise linear approximation expresstion can be obtained

$$\begin{aligned} c_l = \frac{W_l}{\ln 2} \{ m_l^{(k)} [\frac{P_l G_l}{\sigma^2} \quad & - x_l^{(k-1)}] + \ln[1 + x_l^{(k-1)}] \}, \\ & k = 1, ..., K_l, l \in \mathcal{L}, \end{aligned} \tag{17}$$

where K_l represents the total number of segments and the slope of the k-th linear segment is denoted as

$$m_l^{(k)} = \frac{\ln(1 + x_l^{(k)}) - \ln(1 + x_l^{(k-1)})}{x_l^{(k)} - x_l^{(k-1)}}.$$

If the number of linear segments is enough, the error of the linear approximation will be very small; otherwise, if the number of segments are very large and the computational complexity is very high. Theorectically, the number of segments can be obtained when an approximation error of each linear segment is prescribed. By using (18) to replace the nonlinear constraints in (13), the three MINLP problems, **OPT**, **MIN-MAX**, and **OPT-F**, can be transformed into three MILP problems which can be efficiently solved by an off-the-self solver such as CPLEX [25]. Hence, after obtaining the results, the routing, flow rate, and power can be determined accordingly.

4 AN ENERGY-AWARE ROUTING ALGORITHM DESIGN

Although the routing, flow rate, and power can be obtained through solving MINLP problems, much time is taken to solve MINLP because the high computation complexity. Hence, this solution can not be applied in practical multi-hop WMNs with renewable energy, especially the large-scale one. This section presents an energy-aware routing algorithm (EARA) with the consideration of flow rate and power allocation which can achieve the joint control of routing, flow rate, and power with no need of solving MINLP problems and its computation complexity is controllable. We can control the computation time according to the accuracy requirements. As a result, the computation complexity can be reduced significantly. Moreover, the energy consumption and residual energy are simultaneously considered and a balance between them can be attained. It is noteworthy that a multi-path routing is considered here and the split flows meet the rate balance.

In this algorithm, a weighed Dijkstra's shortest path algorithm is exploited to find the optimal routing. The weight is used to integratedly evaluate the energy consumption for data transmission over a link and residual energy of its corresponding transmission node and receiving node. In a word, the weight should have the following properties: 1) It can reflect the energy consumption when a session flow is delivered over a link, which is relative to the flow rate and channel quality; 2) It should be inversely proportional to the residual energy of the transmission node and receiving node. The weight

Algorithm 1 The Energy-aware Routing Algorithm (EARA)

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Initialization:
    Initialize the number of unit flows $N(f)$, the number of unit flows which have been allocated $num(f)$, unit flow rate $\delta$, link rate $r_l = 0$, the routing of each flow $r_l(f)$ and residual energy of each node $B_i$ $(i \in \mathcal{N}, l \in \mathcal{L}, f \in \mathcal{F})$, and set all the sessions flag $flag(f) = true$.
    At the beginning of time slot $t$, all sleep nodes are removed from network $G$ and a new network topology $G_t$ is constructed.
    Calculate the maximum channel capacity for each link $c_l^{max}$ according to (11).
Main Loop:
1: If all sessions satisfy $flag == false$ , go to Step (6).
2: For all links, if link $l \in \mathcal{L}$ satisfies $r_l + \delta > c_l^{max}$, remove $l$ from network $G_t$.
3: Compute weight $w_l$ for each link in network $G_t$ with (21).
4: The weighted Dijkstra's shortest path algorithm is used to find a shortest path for each active session and choose the session (e.g., $f$) whose shortest path has the minimum weight to allocate a unit flow.
5: Update $r_l$, $num(f) = num(f) + 1$. If $num(f) >= N(f)$, $flag(f) = false$ is set and flow $f$ is remove.
6: Merge all unit flows and compute the power consumption through (10) for each node.
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of link l, represented by w_l, is defined as follows

$$w_l = \frac{(P_l + P_{rec}) \cdot T}{A_i A_j}, \tag{18}$$

where $A(i) = B(i)/\sum_{i \in \mathcal{N}} B_i$ indicate the energy level of node i.

As shown in (18), the power consumption and residual energy are contributed to the weight expression. Since the value of w_l can imply the energy consumption and residual energy and the flow rate has a direct relationship to the power allocation, the energy-aware routing problem with the objective of minimizing network-wide energy consumption under network throughput constraint can be transformed into finding a weighed shortest routing problem in multi-hop WMNs with renewable energy.

However, the Dijkstra's shortest path algorithm can only support single-path routing rather than multi-path routing algorithm. Thus, the algorithm should address this problem so as to support multi-path routing. In order to deal with this problem, the concept of unit flow is proposed in this algorithm.

The unit flow is an abstract data flow with a constant flow rate. It is an atom flow that can not be split again to route over multiple paths. The unit flow has a fixed rate whose value is related to accuracy and computation complexity requirements. Let δ denote the unit flow rate and a session flow is usually composed of several unit flows. For a session flow f with $N(f)$ unit flows, its flow rate $r(f)$ is

$$r(f) = \delta \cdot N(f). \tag{19}$$

A session flow consisted of two unit flows performance for multipath, if and only if the two unit flows pass through different paths. By introducing unit flow, the multi-path routing problem for a session flow has become a single-path routing problem for multiple unit flows. The weighted Dijkstra's shortest path algorithm will be executed to find a routing for a unit flow. Therefore, for a session flow f with $N(f)$ unit flows, the weighted Dijkstra's shortest path algorithm should be executed $N(f)$ times.

As shown in (18), in order to get the weight of each link, we must compute the transmission power P_l first. Here, P_l can be obtained by transforming the Shannon formula

$$P_l \geq (2^{\frac{r_l'}{W_l}} - 1)\frac{\sigma^2}{G_l}, \tag{20}$$

where $r_l' = r_l + \delta$ indicate the expected rate when link l with rate r_l is allocate a unit flow. By combining (18) and (20), we define

$$w_l = \frac{((2^{\frac{r_l+\delta}{W_l}} - 1)\frac{\sigma^2}{G_l} + P_{rec}) \cdot T}{A_i A_j}. \tag{21}$$

In addition to the routing and flow rate, the power consumption can also be obtained through the relationship of power consumption and data rate. Hence, once the routing of each unit flow is determined, the routing, flow rate, and power consumption will be determined.

At the beginning of finding a routing for a unit flow, the weight should be updated before a weighted Dijkstra's shortest path algorithm is executed. Since the weight depends on the link rate and residual energy, the weight of a link changes as a unit flow is allocated to this link. At the beginning of each time slot, the nodes whose residual energy is lower than B_{outage} are removed and enter the loop. First, the weight for each link is calculated and the weighted Dijkstra's shortest path algorithm is executed for each session flow. In this way, the shortest path for each session can be found, such as, Path_1, Path_2, ..., Path_f, ..., $f \in \mathcal{F}$. Then, all searched paths for all session flows are compared and a path f with the least weight is assigned a unit flow, such as Path_f. Then the link rate is updated, the link whose data rate is met is removed, and a new loop starts. In the process of executing this algorithm, if the sum of data rate of a link l and δ exceeds the maximum capacity c_l^{max}, link l will be removed from the network. That is to say, link l has been allocate too many unit flows to allocate another. It is noteworthy that a unit flow is allocated in each loop and the weight of each link must be updated as well. This process does not cease until all unit flows of all sessions have been assigned.

The energy-aware routing algorithm for each time slot is summarized in Algorithm 1.

TABLE 1
Each Flow's Source Node, Destination Node, and Rate Requirement and Unit Flow Rate.

Session f	Source node $s(f)$	Destination node $d(f)$	Rate requirement $r(f)$	Unit Flow Rate δ
1	1	12	3.0	0.01
2	2	15	4.0	0.01

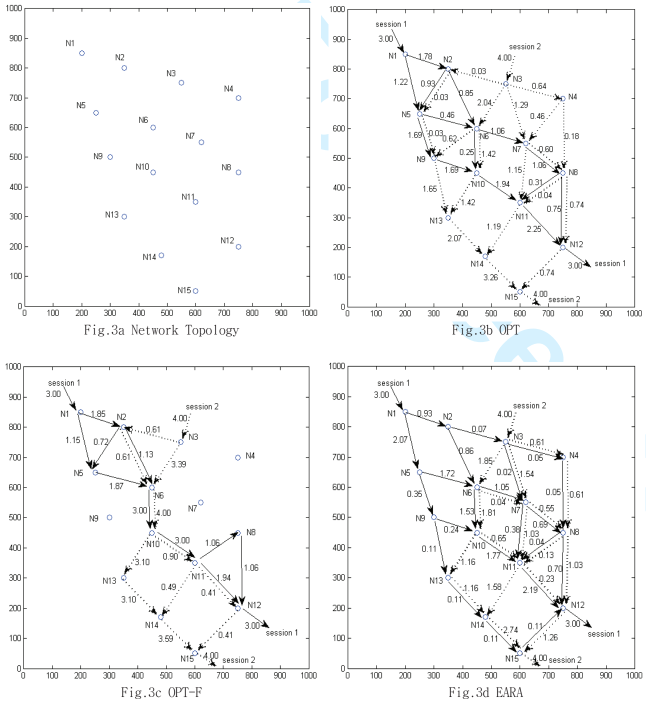

Fig.3a Network Topology

Fig.3b OPT

Fig.3c OPT-F

Fig.3d EARA

Fig. 3. Network topology of a 15-node multi-hop wireless mesh network.

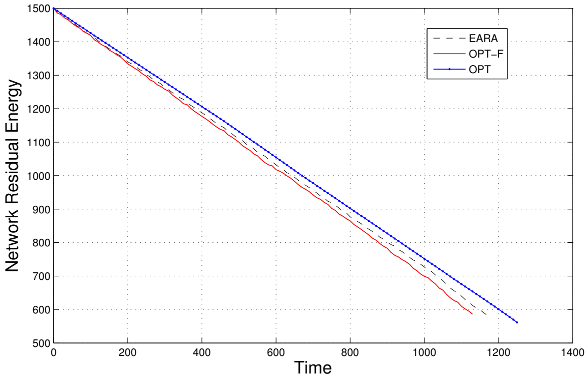

Fig. 4. The change of the total residual energy along the time.

5 SIMULATION RESULTS AND PERFORMANCE ANALYSIS

This section aims to verify the proposed algorithm and investigate the performance of the proposed scheme in multi-hop WMNs with renewable energy through simulation experiments. The considered network scenario is that a randomly generated multi-hop WMNs with renewable energy is deployed in a $1000m \times 1000m$ square area. The maximum transmission power is $P_{max} = 2w$ and the receiving power is $P_{rec} = 0.2w$. Since the multi-hop WMN is considered as a time-division system, the energy consumption can be seen as the power. Hence, the outage energy threshold is prescribed as the output power, $B_{outage} = 10w$ and the maximum output power is $B_{max} = 100w$. The initial energy of each nodes in mult-hop WMNs is random number among [0, 100] when a network scenario is generated. The rate of replenishing energy is $R(t) = 0.02w/(slot)$. The channel bandwidth is $W_l = 1MHz$ for all links and channel gain is a random number among [5dB, 30dB]. Within this network scenario, there are several sessions and source node and destination node of each session are chosen randomly. The required throughput for each session is set as $U = 7Mbps$.

5.1 The Routing and Flow Rate Allocation

This subsection will show the routing and rate allocation in the network scenario as decribed in Fig. 3a where a 15-node multi-hop WMN is randomly generated. The initial residual energy is set as $B = [80, 40, 70, 30, 80, 60, 35, 60, 20, 60, 70, 60, 40, 60, 90]$. There are two sessions in the network scenario and relative parameters are set as shown in Table 1.

Figs. 3b, 3c, and 3d compare the routing and flow rate allocation for **OPT**, **OPT-F**, and **EARA**. The routings and flow rates of session 1 and 2 are shown in each subfigures. Fig. 3 shows that flow routing for session 1 and 2 are all multi-path and multi-hop. It can easily be validated that the flow rates satisfy session flow conservation. In addition, it can be seen that session 1 and 2 always choose the path with minimal energy consumption as long as flow rate does not exceed the maximum capacity in **OPT** algorithm, **OPT-F** algorithm and **EARA** algorithm. This figure shows that the proposed scheme is effective and can achieve efficient routing and rate allocation.

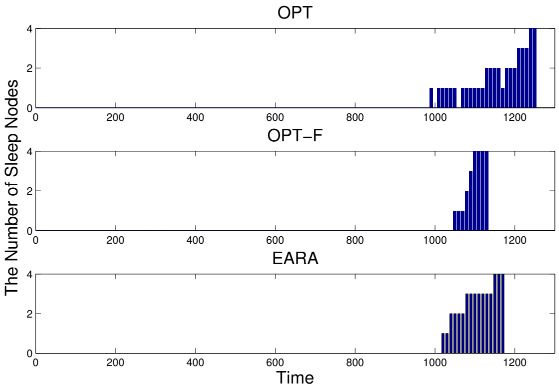

Fig. 5. The change of the number of sleep nodes along the time.

5.2 Dynamics of Total Residual Energy and The Number of Sleep Nodes

Figs. 4 and 5 depict the change of total residual energy and the number of sleep nodes along the time, and show the difference of the total residual energy and the number of sleep nodes in **OPT**, **OPT-F**, and **EARA** algorithms. A 15-node multi-hop WMNs is considered in these two examples and several session flows are perpetually delivered over the network. In order to avoid source node and destination node entering into sleep mode, the source node and destination node periodically change.

Fig. 4 shows that the total residual energy is continually degrading along the time. The reason is that the energy is consumed to deliver two session flow while the energy replenishment rate is much less than the energy consumption rate. In addition, **OPT** algorithm has the highest residual energy among these three algorithms. This is because **OPT** algorithm can achieve the minimal energy consumption without consideration of fairness whereas **OPT-F** and **EARA** can obtain the balance between the residual energy and energy consumption owing to the consideration of fairness among nodes in multi-hop WMNs. Moreover, though the residual energy of **OPT-F** algorithm is less than that of **EARA**, the two curves are much close. This figure indicates that the proposed algorithm can work well in practical multi-hop WMNs and can achieve the similar performance.

Fig. 5 illustrates the change of the number of sleep nodes along the time and shows the difference of these three algorithms. It can be seen from Fig. 5 that the number of sleep nodes is increasing along the time. Meanwhile, the number of sleep nodes of **OPT** algorithm is more than that of **OPT-F** algorithm and **EARA** algorithm, but the network using **OPT-F** algorithm and **EARA** algorithm stop earlier than that using **OPT** algorithm. In this paper, the network lifetime is defined as that the residual energy of the whole network is less than 30

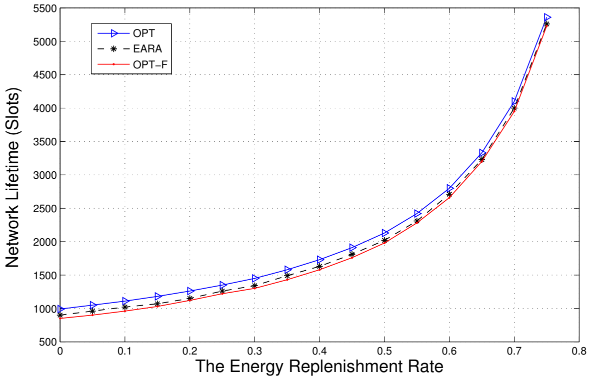

Fig. 6. The effect of energy replenishment rate on network lifetime.

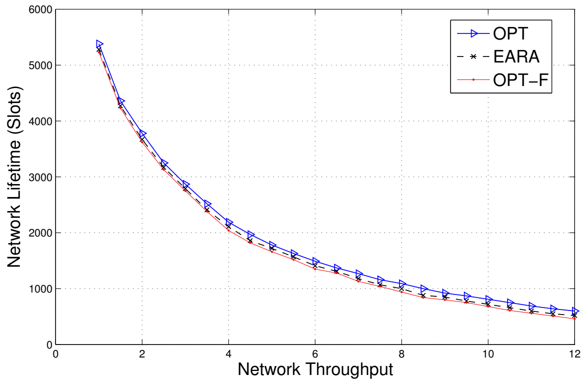

Fig. 7. The effect of throughput on network lifetime.

5.3 Effect of Energy Replenishment Rate on Network Lifetime

This subsection investigates how the energy replenishment rate affects the network lifetime in multi-hop WMNs with renewable energy. Fig. 6 illustrates the effect on the network lifetime. The energy replenishment rate is varied in this simulation experiment and other parameters are set the same as described above.

Fig. 6 depicts the change of the network lifetime with the increasing of the energy replenishment rate and compare the network lifetime with different algorithms. As shown in this figure, the network lifetime with the increase in the energy replenishment rate. Owing to the increasement of the energy replenishment rate, the residual energy of each node increases so that the network lifetime can be extended. In addition, **OPT** can achieve the highest network lifetime because the energy consumption of **OPT** is least among these three algorithms. It can also be seen that the curve of **EARA** is close to **OPT-F**, which means that the proposed algorithm can work very well and achieve almost same routing, rate control, and power allocation.

5.4 Effect of Throughput on Network Lifetime

Fig. 7 reveals the effect of the throughput required by users on network lifetime in multi-hop WMNs with renewable energy. In this simulation experiment, the throughput requirement is changed and other parameters are set the same as described above.

It can be observed from Fig. 7 that the network lifetime is gradually decreasing with the increase in the throughput. This is because the increasing energy is consumed to deliver the information over multi-hop WMNs with renewable energy when the throughput required by users is increasing, which will leads to more nodes entering into sleep state and reduce the network lifetime. In addition, among **OPT**, **OPT-F**, and **EARA**, the network lifetime by applying **OPT** is the highest. The reason is that the energy consumption by applying **OPT** algorithm is least without the consideration of fairness. Besides, this figure shows that the curve of **EARA** is close to **OPT-F** as well.

6 CONCLUSION

In this paper, the routing, rate control, and power allocation are investigated in multi-hop wireless mesh networks (WMNs) with renewable energy and the problem of network-wide energy consumption minimization under the network throughput constraint is formulated as a mixed-integer nonlinear program (MINLP). Moreover, to address the uneven routing problem which may incur some severe performance issues, fairness is taken into account and the min-max fairness model is applied to address this problem. In addition, since the solution to MINLP problem needs much more time, an energy-aware multi-path routing algorithm (EARA) is proposed to deal with the joint control of routing, flow rate, and power allocation in practical multi-hop WMNs. A weighted Dijkstra's shortest path algorithm is applied to search an optimal routing and the concept of unit flow is proposed to multi-path routing. Extensive simulation results are presented and analysed to investigate the performance of the proposed schemes and evaluate the effects of energy replennishment rate and network throughput on the network lifetime. Future work is in progress to consider other important issues, such as channel allocation and interference management.

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