Energy aware routing algorithm of Green communication in Energy Renewable Wireless Mesh Networks

M. Sudharsan, Thiagarajar College of Engineering
Ms.R.Jananee, PSNA College of Engineering & Technology
C. Yaamini, Sethu College of Engineering & Technology
Jananee.rajarani@gmail.com

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 and power still have to be well investigated with the objective of minimizing energy consumption in multi-hop energy renewable wireless mesh networks (ER-WMNs). Due to the high computational complexity of the formulated mathematical programming problem, an energy-aware multi-path routing algorithm (EARA) is proposed to deal with the joint control of routing 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 replenishment rate and network throughput on the network lifetime.

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

I. INTRODUCTION

The increasing demand for ubiquitous network access leads to the rapid development of wireless access technologies. 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 the enhancement of Internet connectivity for mobile users for its provision of high data rate [1]. A multi-hop WMN is usually constructed by wireless mesh nodes that are wireless mesh routers or gateways. One of the features of WMNs is that mesh nodes are rarely mobile and powered by power grid. Mobile users access Internet service through gateway and information is always delivered by virtue of multi-hop relaying.
In the past years, researchers largely concentrate on the channel assignment, routing, and rate allocation problems in multi-hop WMNs [2], [3], [4].

On the other hand, the power grid infrastructure, which provides electricity to multi-hop WMNs, has been experiencing a dramatic change from the traditional electricity grid to the smart grid where renewable energy is integrated [5], [6]. 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. Obviously, the use of renewable energy, to some extent, can alleviate the greenhouse gas emission problem. Therefore, renewable energy will play a vital role in future wireless network infrastructures (e.g., wireless mesh networks).

However, the problems of routing and power allocation still have to be well investigated when renewable energy is exploited in multi-hop WMNs because renewable energy replenishment of each node in multi-hop WMNs is highly dependent on the environment. Such WMNs are also denoted as energy renewable WMNs (ER-WMNs) in this paper.

Although some related research work has been conducted on problems in ER-WMNs, the high interdependency of routing and power, and their significant influence on energy consumption in multi-hop WMNs have been little studied. To fill in this vacancy, this paper proposes a scheme that jointly considers routing and power allocation to minimize network wide energy consumption with network throughput constraint in multi-hop ER-WMNs. The key contributions of this paper are summarized as follows.

- ✓ The problem of network-wide energy consumption minimization under network throughput constraint in multi-hop ER-WMNs is investigated.
- ✓ 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 due to their low residual energy level, in multi-hop ER-WMNs compared to traditional multi-hop.
- ✓ Due to the high computational complexity to solve the MINLP formulation, an energy-aware multipath routing algorithm (EARA) is proposed to practically deal with the joint control of routing and power in multi-hop WMNs.

II. SYSTEM MODEL

A. NETWORK MODEL

This paper considers a multi-hop ER-WMN, represented by a directed graph G = {N,L} where N and L are the sets of nodes and directional links, respectively. A link between two nodes exists if and only if the two are within a certain communication range. The communication between two nodes 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. In addition, the time-division system is considered here, where 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 so that the routing and power allocation cannot be affected.

In particular, each node is powered only by renewable energy in multi-hop ER-WMNs and the solar is considered as the energy source. A large-sized solar panel is used to obtain the solar energy that is then transformed into electrical energy. The structure of a node is shown in Fig. 1, where a solar panel connects the access point (AP). The electrical energy will be stored into the battery via a charging controller that controls the charging process. Each node consumes the energy from the battery because it can supply the energy continuously. Once the energy contained in the battery is lower than a threshold, the charging controller will immediately shut down the power supply and the node enters sleep mode. Since the energy production rate is low in practical energy systems, the energy replenishment rate is less than the energy consumption rate when a session is delivered through a node.

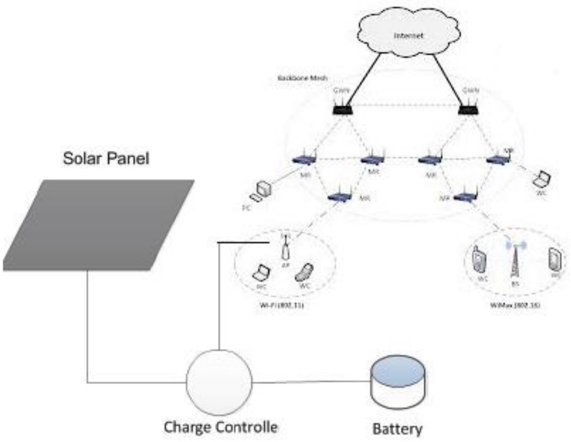

Figure 1.The structure of the node powered by solar energy

B. SESSION FLOW MODEL

Suppose a set of F active unicast sessions in the considered network scenario. Let s(f) and d(f) denote the source and destination nodes of session f respectively. Moreover, r(f) represents the data rate of session f. Therefore, for the network with |f| active session flows, network throughput U is the sum of data rate of all sessions, i.e.,

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

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

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

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

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

If node i is an intermediate node of session f, i.e.,

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

Since the quality of service (QOS) for each user needs to be guaranteed in multi-hop ER-WMNs, the data rate of each session should be met in the design of the joint routing, rate control, and power allocation scheme.

C.POWER AND ENERGY CONSUMPTION MODEL

In general, when a session is delivered on a link in multi hop ER-WMNs, the energy is mainly consumed due to data transmission and reception. The receiving power is denoted by P_{rec}, which is considered as a constant in this paper. 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 rate allocation. Let X_l be a binary variable indicating whether link l is active or not, i.e.,

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

Hence, the energy consumption for link l is (P_l+X_l_Prec). The maximum transmission power for each node is defined as P_{max} and the transmission power cannot exceed the maximum transmission power

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

Since there are several potential outgoing links at node i, the transmission power constraint can be expressed as follows

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

Let E_i denote the total energy consumption at node I during a time slot, and it is expressed as follows

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

The data rate of a link is constrained by its theoretical capacity that can be obtained through Shannon formula, i.e.,

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

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 $c^{max}{}_l$ is

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

III. PROBLEM FORMULATION

AN ENERGY-AWARE ROUTING ALGORITHM DESIGN

Although routing and power can be determined through solving MINLP problems, much time is still needed to solve large-scale problems [7]. This section presents an Energy-Aware Routing Algorithm (EARA) with the consideration of flow rate and power allocation. This algorithm can achieve the joint control of routing and power with no need of solving MINLP problems. The computational complexity of the proposed EARA is controllable, and can be adjusted according to the accuracy requirements. As a result, the algorithm can be well applied in the practical multi-hop ER-WMNs. Moreover, the consumed energy 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. Since the energy consumption and residual energy should be jointly considered, the weight should have the following properties: 1) it can reflect the energy consumption relating to the flow rate and channel quality, and 2) it should be inversely proportional to the residual energy of the transmission node and receiving node. The weight of link l, represented by w_l, is defined as follows

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

As shown the power consumption and residual energy are contributed to the weight. Since the value of w_l can reflect the consumed energy and residual energy, 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 ER-WMNs.

However, the weighted Dijkstra's shortest path can only support single-path routing rather than multi-path routing. Thus, this problem should be addressed to make this algorithm 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 atomic flow with a constant flow rate, and cannot be split further when it is delivered in ER-WMNs. The selection of constant flow rate depends on the accuracy and computational complexity requirements. For session f with N(f) unit flows, its flow rate r(f) is

$$r(f) = \delta \cdot N(f).$$

By introducing the concept of unit flow, the multi-path routing problem for a session 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 session f with N(f) unit flows, the weighted Dijkstra's shortest path algorithm should be executed N(f) times.

IV. SIMULATION RESULTS

This section aims to investigate the performance of the proposed algorithms EARA, in multi-hop ER-WMNs by virtue of simulation experiments. The considered network scenario is that a randomly generated multi-hop ER-WMN is deployed in a 1000m*1000m square area. The Maximum transmission power is Pmax = 2w and the receiving power is Prec = 0.2w. Since the multi-hop WMN is considered as a time-division system, the energy consumption can be seen as the allocated power. Hence, the outage energy threshold is prescribed as the output power, Boutage = 10w and the maximum output power is Bmax = 100w. The initial energy of each node in mult-hop WMNs is random number among [0, 100] when a network scenario is generated. The energy replenishment rate is r(t) = 0:02w=(slot), and identical for all nodes. The channel bandwidth is Wl = 1MHz for all links and channel gain varies between 5dB and 30dB. Within this network scenario, there are several sessions and the source node and destination node of each session are chosen randomly.

A. Dynamics of Total Residual Energy and The Number of Sleep Nodes

Figs. 2 and 3 depict the changes of total residual energy and the number of sleep nodes along the time in EARA algorithm. A 15-node multi-hop WMN is considered in these two examples and several sessions are perpetually delivered over the network. In order to avoid the selected source node and destination node entering into sleep mode, the sessions occur randomly and periodically change.

Fig. 2 shows that the total residual energy is continually degrading along the time. The reason is that the energy is consumed to deliver two sessions while the energy replenishment rate is much less than the energy consumption rate.

Fig. 3 illustrates that the number of sleep nodes is increasing along the time. The network lifetime, i.e., the duration of delivering sessions, is less in EARA algorithm. In this paper, the lifetime is defined as the network operation time until the residual energy of the whole network is less than 30%. The reason is that much more energy is consumed by EARA algorithms, so some nodes can easily enter sleep mode after a duration.

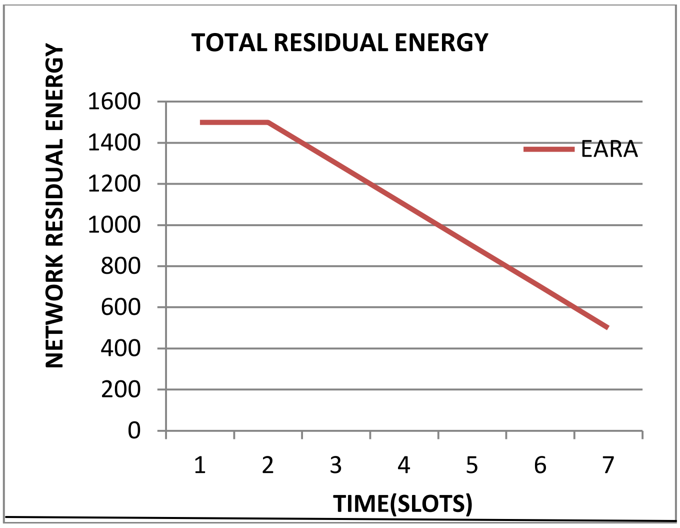

Fig 2. The change of the total residual energy along the time.

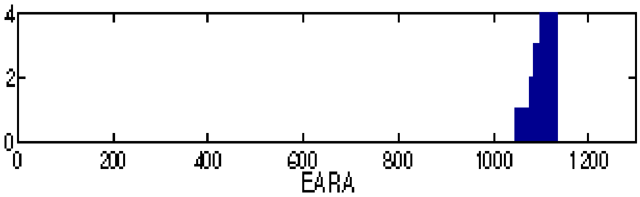

Fig 3. The change of the number of sleep nodes along the time.

Fig. 3 illustrates that the number of sleep nodes is increasing along the time. Moreover, the network lifetime, i.e., the duration of delivering sessions, if using the EARA algorithm. In this paper, the lifetime is defined as the network operation time until the residual energy of the whole network is less than 30%. The reason is that much more energy is consumed by EARA algorithms, so some nodes can easily enter sleep mode after a duration.

B. Effect of Energy Replenishment Rate on Network Lifetime

Fig. 4 illustrates the effect of the energy replenishment rate on network lifetime in multi-hop ER-WMNs. The energy replenishment rate varies in this simulation experiment and other parameters are set the same as described above.

Fig. 4 depicts the change of the network lifetime with the increasing of the energy replenishment. As shown in this figure, the network lifetime is increasing when the energy replenishment rate grows. Owing to the increment of the energy replenishment rate, the residual energy of each node increases so that the network lifetime can be extended.

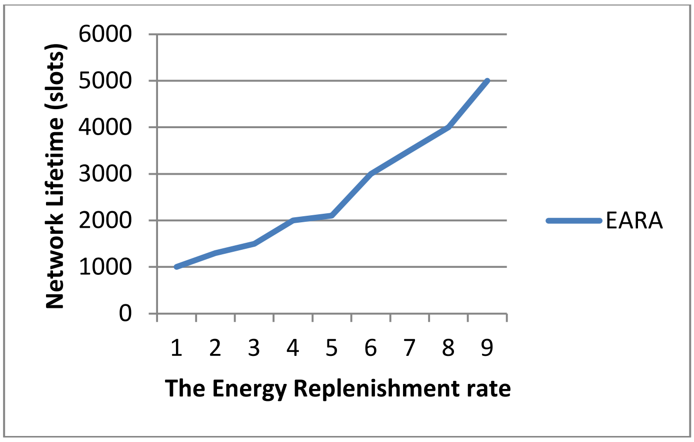

Fig 4. The Effect of Energy replenishment on network lifetime

C. **Effect of Throughput on Network Lifetime**

Fig. 5 reveals the effect of the throughput required by users on network lifetime in multi-hop ER-WMNs. In this simulation experiment, the throughput requirement varies and other parameters are set the same as described above.

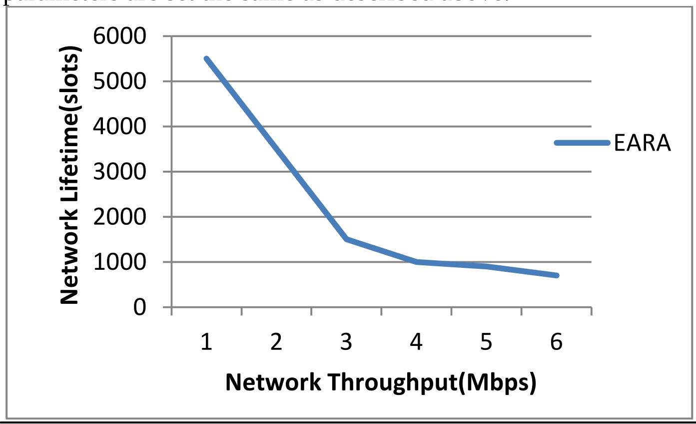

Fig 5. The effect of throughput on network lifetime

It can be observed from Fig. 5 that the network lifetime is gradually decreasing with the increase of the throughput. This is because more energy will be consumed to deliver the information over multi-hop ER-WMNs when the throughput required by users is increasing, resulting in that more nodes will enter into sleep mode and the network lifetime will be reduced. In addition the EARA algorithm can achieve the highest network throughput. The reason is that the energy consumption by applying the EARA algorithm is lowest due to consideration of the balance of energy consumption and residual energy.

V. CONCLUSION

In this paper, the routing and power allocation are investigated in multi-hop energy renewable wireless mesh networks and the problem of network wide energy consumption minimization under network throughput constraint is formulated in a form of MINLP. To address the uneven routing problem which may incur some severe performance issues, fairness is taken into account. In addition, solving the MINLP problem would time prohibitive, an energy-aware routing algorithm EARA is proposed to deal with the joint control of routing and power in practical multihop ER-WMNs. A weighted Dijkstra's shortest path algorithm is applied to search an optimal routing. Furthermore, the concept of unit flow is proposed such that our Dijkstra-based algorithm can support the multipath routing. Extensive simulation results are presented and analysed to show the performance of the proposed schemes.

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