Wireless Netw
DOI 10.1007/s11276-015-0991-3

Joint relay assignment and rate–power allocation for multiple paths in cooperative networks

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Abstract Multi-path transmission is an efficient way to balance the power consumption from a source to a destination. The previous works have studied rate–power allocation to prolong the network lifetime of multiple paths. As at least one relay node is required to participate into cooperative transmission, its assignment will greatly impact the power consumption of cooperative communication. Thus, this paper addresses the joint resource allocation problem which aims to prolong the lifetime of multi-path cooperative transmission. Given a path set from a source to a destination, we first define the lifetime-optimal relay assignment and rate–power allocation problem (LRRP) for multiple paths with cooperative communications. This paper then presents two heuristic algorithms, called BS-RRP and PS-RRP, to implement efficient resource allocation for multiple paths. The BS-RRP algorithm uses the binary search method to solve the LRRP problem on node-disjoint paths, and reaches the approximate performance $1-\varepsilon$, where ε is an arbitrarily small positive constant. PS-RRP adopts the pattern search method for joint resource allocation on link-disjoint paths, and terminates after finite iterations. The simulation results show that the BS-RRP and PS-RRP algorithms can improve the network lifetimes about 26 and 30 % compared with the resource allocation methods under the non-cooperative communication scheme.

Keywords Relay assignment · Rate–power allocation · Cooperative communication · Multiple paths

1 Introduction

In this paper, we study the lifetime maximization of multiple paths with cooperative communications for wireless ad-hoc networks. Considering a video surveillance application, the camera nodes will report the monitoring information to the control center through multiple disjoint paths [1]. For long-time surveillance, it is a critical challenge to prolong the network lifetime. Usually, the source node knows a set of routes that will reach the destination node. The possible paths can be discovered by applying previous routing protocols, such as [2, 3]. The advantage of using multiple disjoint paths is two-fold [4]: (1) in case of route failure, the source is still able to transmit data to the destination by the substituted routes, and node or link faults will not affect other paths in the disjoint routing; and (2) it provides an even distribution of the traffic load or energy drain over a network.

With the constraints of node size and deployment environment, resource-constraint is an important feature for ad hoc networks, which may result in lower

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transmission quality [5]. For example, since batteries can only supply a finite amount of energy, it is a major task in such networks to minimize the node's power consumption for wireless communication and traffic processing. Another important resource category is bandwidth of each wireless link, which impacts achievable transmission rates for different services. However, wireless transmission with high rate also leads to massive power consumption. The previous works [4, 6–8] have shown that resource allocation was an efficient way to achieve lifetime maximization. For example, rate allocation among multiple paths will affect the fairness of power consumption among all nodes. To balance the energy consumption among multiple paths, the source node does not uniformly allocate the rate among all the paths. On the contrary, efficient rate allocation mechanisms are adopted to satisfy the performance requirements, such as maximum network lifetime, etc. Thus, the topic of joint rate and power allocation has been deeply studied [4, 6, 7, 9, 10].

Recently, *cooperative communication* [11–17] is shown to be a promising technology to efficiently improve spatial diversity. Under this communication paradigm, each node only needs to be equipped with a single transceiver antenna and multiple nodes are allowed to coordinate their transmissions so as to save the power cost of wireless communication. For convenience, non-cooperative communication is also called as *traditional communication*. There are two main modes of cooperative communication, amplify-and-forward (*AF*) and decode-and-forward (*DF*) [13], respectively. Under the *AF* mode, the cooperative relay performs a linear operation on the received signal from the source node, then forwards the signal to the destination node. Under the *DF* mode, the cooperative relay first decodes the received signal, re-encodes it, and forwards it to the destination node. As at least one relay node is required to participate into cooperative transmission, it becomes a special resource category under the cooperative communication. The next section will describe the formal capacity expressions for different communication modes. The theoretical analyses show that, under the fixed transmission power on each node, the cooperative communication with appropriate relay selection is able to offer an increased capacity than that under the non-cooperative scheme for a source–destination pair [11]. However, a poor choice of relay node may decrease the transmission capacity. Therefore, relay assignment will affect the achievable rate and power consumption for cooperative routing [11, 18, 19], thus also impacting the network lifetime.

According to the above description, relay, rate and power are three categories of important resources in wireless cooperative networks, and their usage will impact the network lifetime greatly. There are some works [4, 6] on joint rate and power allocation for lifetime maximization on disjoint multiple paths. However, these methods do not explore the benefit of cooperative communications. Therefore, this paper studies the joint relay assignment and rate–power allocation for disjoint multiple paths aiming to prolong the network lifetime. The main contributions of this paper are as follows:

1. An efficient power allocation method between a transmitter and a relay is designed to obtain the maximum node lifetime while providing the required rate for different communication schemes.
2. Based on power allocation analyses, we define the lifetime-optimal relay assignment and rate–power allocation for multiple paths (LRRP) problem in cooperative networks, and formalize this problem into a non-linear program.
3. This paper presents two heuristic algorithms, called BS-RRP and PS-RRP, to implement joint resource allocation for multiple paths. The BS-RRP algorithm adopts the binary search method to solve the LRRP problem on node-disjoint paths, and reaches the approximate performance $1-\varepsilon$, where ε is an arbitrarily small positive constant. PS-RRP uses the pattern search method for resource allocation on link-disjoint paths, and terminates in finite iterations.
4. The simulation results show that the BS-RRP and PS-RRP algorithms can prolong the network lifetimes about 26 and 30 % compared with the traditional methods under many situations.

The rest of this paper is organized as follows. In Sect. 2, we discuss the related works about the resource allocation problem. Section 3 describes the cooperative communication model and problem definition. Section 4 presents the BS-RRP algorithm to solve the LRRP problem for node-disjoint paths, and analyzes its performance. In Sect. 5, we design the PS-RRP algorithm for link-disjoint paths. Section 6 illustrates the simulation results. We conclude the paper in Sect. 7.

2 Related works

Under the non-cooperative communication scheme, some previous works [4, 6, 7, 9] focused on joint rate and power allocation for multiple paths. In Hou et al. [4], studied the lexicographical max–min rate allocation among all nodes with system lifetime requirement. The authors in [6] used penalty functions to solve the problem while taking the system constraints into account. The proposed approach led to a flow control algorithm, which provided the optimal source rates and could be easily implemented in a distributed manner. The authors in [7] enforced fairness on source rates of sensor nodes by invoking the network utility maximization framework, and formulated the rate allocation fairness as a constrained maximization problem. Chou et al. [8] studied a more general problem in which the routing of flows, possibly over multiple paths per flow, was an optimization parameter for the rate allocation problem. They evaluated the proposed algorithms on a statistical traffic application to show that higher utility could be achieved when multi-path routing was considered with rate allocation under utility max–min fairness. The above algorithms [4, 6–8] considered the rate–power allocation for multiple paths to obtain the required network performance under the traditional communication scheme. The authors in [9, 10] studied rate allocation among all the nodes in a network to maximize the network lifetime, which was different from our focus.

Recently, the cooperative transmission paradigm is regarded as an emerging technology for future wireless communications. Since relay is an important resource category for cooperative communications, we pay our main attention on relay assignment in the cooperative networks. The authors in [18] studied the selection of an optimal relay node for a source–destination pair. Zhao et al. [19] showed that it was sufficient to choose the best relay node for a transmission pair to achieve full diversity. Moreover, the cooperation among multiple nodes needed the complex management and precise time synchronization. Our work also assumes that at most one relay will participate into cooperative transmission from a transmitter to a receiver.

For wireless multi-hop networks, Khandani et al. [20] studied the minimum energy routing problem by exploiting the advantages of wireless broadcast and cooperative communication. They developed a dynamic program based solution and two heuristic algorithms to find the energy-minimum routes. Luo et al. [13] proposed an energy-efficient joint relay selection and power allocation scheme for cooperative communication. They designed a solution through a first-order relaxation method and a primal–dual priority-index heuristic. Zhou et al. [15] also focused on energy minimization through relay selection and power control. However, these approaches just focused on individual traffic as opposed to multiple paths that we considered in this paper. Scaglione et al. [21] designed two architectures for multi-hop cooperative networks. Under these architecture frameworks, all nodes in the network formed multiple cooperative clusters. They showed that the network connectivity could be improved by using such cooperative clusters. Two works [12, 17] studied the energy-efficient clustering for cooperative data forwarding. Xie et al. [14] designed an efficient algorithm to minimize the total consumed power of the network while guaranteeing transmission reliability of multiple active transmission pairs through cooperative communications. The work [16] also aimed to improve the transmission reliability through relay-power allocation. However, problems related with LRRP are not the focus for their works.

As mentioned above, the previous works [4, 6, 7, 9, 10] for joint rate and power allocation do not take the cooperative communication into considerations. Thus, they can not explore the advantages of spatial diversity by cooperative communications. The works on relay assignment are not fit for the LRRP problem. The reason is that most works assume that each node uses the fixed power [19] or the required rate on each path is fixed [22]. However, relay assignment and rate–power allocation will all impact the network performance under cooperative communications. Thus, this paper studies the joint resource allocation for multiple paths to fully improve the performance of wireless ad hoc networks.

3 Preliminaries

This section will describe the cooperative communication model, lifetime-aware power allocation mechanism and problem definition. For ease of explanation, a list of important symbols used in this paper is summarized in Table 1.

3.1 Cooperative communication model

We illustrate the cooperative communication by an example of three nodes. As shown in Fig. 1, vertices s, r and d represent the source node, relay node and destination node, respectively. Wireless transmission from node s to node d is based on the frame-by-frame mechanism [11]. It usually costs two time slots to transmit one frame. In the first time slot, node s transmits a frame to destination node d. Due to wireless broadcast feature, it is also overheard by relay node r. In the second time slot, node r forwards the received data to node d.

In the following, we introduce the mathematical expressions of capacity under different communication schemes. First, the signal–noise-ratio SNR_{sd} from node s to node d is defined as [20]:

$$SNR_{sd} = \frac{p_s * h_{sd}^2}{\sigma_d^2} \tag{1}$$

There are two main forwarding modes of cooperative communications. Under the AF mode, the capacity from node s to node d with relay node r is [11]:

$$\begin{aligned} C_{AF}(s,r,d) &= W \cdot I_{AF}(SNR_{sd}, SNR_{sr}, SNR_{rd}) \\ &= \frac{W}{2}\log_2\left(1 + SNR_{sd} + \frac{SNR_{sr} \cdot SNR_{rd}}{SNR_{sr} + SNR_{rd} + 1}\right) \end{aligned} \tag{2}$$

where W is the available bandwidth of a channel. Under the DF mode, the capacity is given as [11]:

Table 1 Index of important symbols

Term	Definition	Term	Definition
p_s	The transmission power of node s	E_u	Initial energy on node u
h_{sd}	The effect of path-loss, shadowing and fading between node s and node d	σ_d^2	Variance of background noise at node d
SNR_{sd}	Signal–noise-ratio from node s to node d	W	Available bandwidth of a channel
V	A node set in the network with $\lvert V\rvert = n$	Q	Rate requirement of multi-path routes
$\Re$	A set with k paths, $\Re = \{\Psi_1, \ldots \Psi_k\}$	L_v	Lifetime of node v
$p_{v_i}^j$	Power consumption of node v_i on path Ψ_j	Ψ_j^i	Sub-path from v_{j_0} to v_{j_i} on Ψ_j
Q_j	Allocated rate for path Ψ_j	Q_j^i	Achievable rate for sub-path Ψ_j^i
$L_j^{\max}$	Maximum lifetime of path Ψ_j	L_j^i	Maximum lifetime of sub-path Ψ_j^i
L_c	Current network lifetime	δ	Step-size for rate adjustment

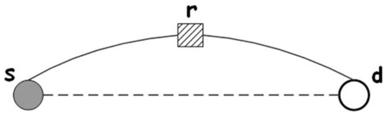

Fig. 1 Illustration of the cooperative communication

$$C_{DF}(s,r,d) = W \cdot I_{DF}(SNR_{sd}, SNR_{sr}, SNR_{rd}) = \frac{W}{2}\min\{\log_2(1+SNR_{sr}), \log_2(1+SNR_{sd}+SNR_{rd})\} \tag{3}$$

When the cooperative communication is not used, node s transmits directly to node d in both time slots. It is just the traditional communication scheme. Thus, the capacity from node s to node d is [11]:

$$C_D(s,d) = W \cdot \log_2(1+SNR_{sd}) \tag{4}$$

There are two observations from the above mathematical expressions. First, comparing these communication schemes, cooperative transmission with proper relay selection will work better than the direct transmission. However, a poor choice of relay node might make the capacity under cooperative communications be worse than that under the direct transmission. That is, the achievable rate can be improved through efficient relay assignment [1]. Second, different transmission powers on source and relay nodes result in different transmission capacities from Eqs. (2–3). Moreover, wireless capacity under the cooperative communication scheme is determined by transmission powers of both source and relay nodes. Thus, efficient power allocation will reduce the power consumption while providing the required rate.

3.2 Lifetime-aware power allocation method

In this section, we will analyze the lifetime-aware power allocation for different communication schemes while providing the required rate Q. The analysis is based on the network example shown in Fig. 1. The variables p_u and E_u denote the assigned transmission power and initial energy for node u. In the following, we study the efficient power allocation for cooperative and direct transmission schemes. Without loss of generality, the achievable rate of each link is equal to its capacity.

Under the AF mode, the achievable rate is expressed in Eq. (2). We consider the critical conditions for rate requirement. That is,

$$\begin{aligned}&\frac{W}{2}\log_2\left(1+SNR_{sd}+\frac{SNR_{sr}\cdot SNR_{rd}}{SNR_{sr}+SNR_{rd}+1}\right) = Q\\ &\Rightarrow 1+SNR_{sd}+\frac{SNR_{sr}\cdot SNR_{rd}}{SNR_{sr}+SNR_{rd}+1} = q\end{aligned} \tag{5}$$

where q is $2^{\frac{2Q}{W}} > 1$. For ease expression, let the variable $\delta_{s,d}$ denote $\frac{h_{sd}^2}{\sigma_d^2}$. Equation (5) also means that:

$$\begin{aligned}&1+p_s\delta_{s,d}+\frac{p_s\cdot\delta_{s,r}\cdot p_r\cdot\delta_{r,d}}{p_s\cdot\delta_{s,r}+p_r\cdot\delta_{r,d}+1} = q\\ &\Rightarrow (1-q)\big(p_s\delta_{s,r}+p_r\delta_{r,d}+1\big)+p_s^2\delta_{s,d}\delta_{s,r}\\ &+p_rp_s\delta_{r,d}\delta_{s,d}+p_s\delta_{s.d}+p_rp_s\delta_{s,r}\delta_{r,d} = 0\end{aligned} \tag{6}$$

To optimize the network lifetime, both source and relay should obtain the same lifetime, so that the minimum lifetime among two nodes is maximized, expressed by $\frac{E_s}{p_s} = \frac{E_r}{p_r}$. This constraint can be simplified into: $p_r = c_{r,s}p_s$, with $c_{r,s} = \frac{E_r}{E_s}$. Thus, a new equation is derived from Eq. (6) as:

$$\begin{aligned}&f(p_s) = \alpha p_s^2+\beta p_s+\gamma = 0, \quad \text{where} \quad \alpha = \delta_{s,d}\delta_{s,r}\\ &\quad +c_{r,s}\delta_{r,d}\delta_{s,d}+c_{r,s}\delta_{s,r}\delta_{r,d},\\ &\beta = (1-q)\big(\delta_{s,r}+c_{r,s}\delta_{r,d}\big)+\delta_{s,d},\\ &\text{and} \quad \gamma = (1-q)<0.\end{aligned} \tag{7}$$

There are two solutions for Eq. (7), denoted by:

$$p_{s,1} = \frac{-\beta + \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}, \quad \text{and} \quad p_{s,2} = \frac{-\beta - \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}. \tag{8}$$

As $\alpha > 0$ and $\gamma < 0$, $p_{s,1} \times p_{s,2} = \frac{\gamma}{\alpha} < 0$. Thus, one solution is positive, the other is negative. As a result, we obtain the transmission power of node s as:

$$p_s = p_{s,1} = \frac{-\beta + \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha} \tag{9}$$

According to the lifetime constraint, the transmission power of node r is:

$$p_r = c_{r,s} p_s = \frac{c_{r,s}\left(-\beta + \sqrt{\beta^2 - 4\alpha\gamma}\right)}{2\alpha} \tag{10}$$

After power allocation for source node and relay node is fulfilled, the node's lifetime is also derived. Under the *DF* mode, the achievable rate is expressed in Eq. (3). To satisfy the rate requirement, the optimal power allocation is as follows:

$$\frac{W}{2}\min\{\log_2(1 + SNR_{sr}), \log_2(1 + SNR_{sd} + SNR_{rd})\} = Q$$
$$\Rightarrow p_s\delta_{s,r} = q - 1, \quad \text{and} \quad p_s\delta_{s,d} + p_r\delta_{r,d} = q - 1 \tag{11}$$

For simplicity, let $\mu = q - 1$. Therefore,

$$p_s = \frac{u}{\delta_{s,r}}, p_r = \frac{\mu(\delta_{s,r} - \delta_{s,d})}{\delta_{s,r}\delta_{r,d}} \tag{12}$$

Under the direct communication scheme, the achievable rate is expressed in Eq. (4). Thus, we have:

$$W \cdot \log_2(1 + SNR_{sd}) \geq Q \tag{13}$$

Obviously, the assigned power for node s should be:

$$p_s \geq \frac{2^{\frac{W}{Q}} - 1}{\delta_{s,d}} = \frac{\sqrt{q} - 1}{\delta_{s,d}} \tag{14}$$

We observe that there is a deterministic power allocation to achieve the optimal lifetime while providing the required transmission rate from transmitter to receiver under different communication schemes. Moreover, the time complexity for power allocation is $O(1)$.

3.3 Lifetime-optimal relay assignment and rate–power allocation problem definition

This section describes the formal definition of lifetime-optimal relay assignment and rate–power allocation (LRRP) problem for multi-path routing in cooperative networks. As wireless nodes are usually resource-constrained, the communication range is relatively short. Thus, we consider a wireless multi-hop network which consists of many nodes in a target filed. For simplicity, all nodes are assumed to be stationary during a session. Each node can potentially act as a cooperative relay.

Given a wireless network, assume that there is a path set $\Re$ from source node s to destination node d. The possible routes from source to destination can be discovered by applying different routing protocols, such as [2, 21]. For each path, we will designate some relay nodes for cooperative transmission so as to save the power consumption and prolong the network lifetime. Zhao et al. [19] have shown that for a single-hop transmission, the obtained diversity gain by exploiting multiple relay nodes was not higher than that by selecting the best relay. As a result, it is reasonable to assume that each transmitter will send to the receiver with one cooperative relay at most [11, 23].

In many applications, such as camera surveillance, it is required to provide the high-quality multimedia transmission service from source (e.g., a camera node) to destination (e.g., a monitoring center). Thus, we regard that source node s can communicate with destination node d through a set $\Re$ of k paths so as to provide an aggregate rate Q. For simplicity, we assume that $\Re = \{\Psi_1, \ldots \Psi_k\}$, and all nodes belonging to path set $\Re$ is denoted by V. The LRRP problem implements the efficient relay assignment and rate–power allocation among all nodes on the paths to prolong the network lifetime. Each path $\Psi_j \in \Re$ will be allocated a non-negative rate Q_j, such that the aggregate rate of all paths is not less than Q, expressed in Eqs. (15, 16). To satisfy the rate requirement, each node $v_i \in \Psi_j$ will be allocated a transmission power $p^j_{v_i}$, which denotes the power consumption of node v_i on the path Ψ_j, such that path Ψ_j can provide a rate Q_j at least. The power allocation will be introduced in the next sections. The total power consumption of node v_i on multiple paths is $p_{v_i} = \sum_{\Psi_j \in \Re} p^j_{v_i}$ by Eq. (17). Then, the lifetime of node v_i is $L_{v_i} = \frac{E_{v_i}}{p_{v_i}} = \frac{E_{v_i}}{\sum_{\Psi_j \in \Re} p^j_{v_i}}$, where E_{v_i} is the initial energy on node v_i. Usually, the lifetime of multiple paths is defined as the time until the first node uses up its energy. Our objective is to obtain the long-time surveillance, expressed by Eq. (19). The problem formulization is described in Table 2.

In wireless multi-hop networks, since multi-path routing can balance the traffic load and prolong the network lifetime, it has received much attention in the recent years, such as [1, 3]. There are two main categories of multi-path routing, node-disjoint and link-disjoint respectively. In the following, we will deal with the LRRP problem corresponding to the different categories of multiple paths.

Table 2 Formalization of the LRRP problem

Constraints	
$Q_j \geq 0$	(15)
$\sum_{\Psi_j \in \Re} Q_j \geq Q$	(16)
$p_{v_i} = \sum_{\Psi_j \in \Re} p_{v_i}^j$	(17)
$L_{v_i} = \frac{E_{v_i}}{p_{v_i}}$	(18)
Objective	
$\max \min\{L_{v_i}, v_i \in V\}$	(19)

4 Algorithm for the node-disjoint multi-path case

This section will present a polynomial-time algorithm to solve the LRRP problem for node-disjoint multiple paths. We call this as binary-search-based relay assignment and rate–power allocation (BS-RRP) algorithm. The theoretical analysis shows that the proposed algorithm can reach the approximate performance of $1 - \varepsilon$, where ε is an arbitrarily small positive constant.

4.1 Algorithm description

For node-disjoint multiple paths, each intermediate node only belongs to one path from a source node to a destination node. We implement the efficient resource allocation for all nodes on multiple paths with the binary search method. First, the BS-RRP algorithm selects the possibly minimal lifetime and maximal lifetime of multi-path routing, denoted by $L_{\min}$ and $L_{\max}$, respectively. For example, $L_{\min}$ is set as 0, and $L_{\max}$ is a large number, such as 10^6. In each iteration, the algorithm determines a middle lifetime as $L_{mid} = \frac{L_{\min} + L_{\max}}{2}$, and will be terminated if $\frac{L_{\max} - L_{\min}}{L_{\max}} < \varepsilon$, where ε is a small positive constant. Otherwise, we compute the achievable rate $Q_{\Psi_j, L_{mid}}$ for each path $\Psi_j \in \Re$ under lifetime constraint L_{mid}, which is the core of the BS-RRP algorithm and described in the next paragraph. If the sum of achievable rates on all paths is less than the requirement Q, the algorithm sets $L_{\max} = L_{mid}$. This means that all nodes should increase the transmission powers so as to improve the achievable rate. In other words, the network lifetime should be reduced. Otherwise, BS-RRP will search a resource allocation solution within a longer-lifetime interval, i.e., $L_{\min} = L_{mid}$. The BS-RRP algorithm is described in Fig. 2.

From the above description, it is an important task to compute the achievable rate of each path under lifetime constraint for the BS-RRP algorithm. In the following, we design a sub-routine, called RLC, to solve this problem. For simplicity, the constructed k node-disjoint paths are denoted by Ψ_1, Ψ_2,…Ψ_k. Assume that $\Psi_j = v_{j_0}(s) v_{j_1} \ldots v_{j_{m-1}} v_{j_m}(d)$, where m is the hop number of path Ψ_j in the traditional sense. Given lifetime requirement L, the maximum transmission power of each node v is $p_v = \frac{E_v}{L}$. We define two variables cq_i and dq_i for each node v_{j_i} on path Ψ_j. The variable cq_i denotes the achievable rate in which node v_{j_i} acts a cooperative relay from node $v_{j_{i-1}}$ to node $v_{j_{i+1}}$. That is, $cq_i = C_{XF}\left(v_{j_{i-1}}, v_{j_i}, v_{j_{i+1}}\right)$ by Eqs. (2, 3), where XF is either AF or DF. Moreover, dq_i represents the achievable rate from node v_{j_i} to node $v_{j_{i+1}}$ under the direct transmission. That is, $dq_i = C_D\left(v_{j_i}, v_{j_{i+1}}\right)$ by Eq. (4). For simple description, Ψ_j^i denotes the sub-path from v_{j_0} to v_{j_i} on the path Ψ_j. Its maximal achievable rate under cooperative communication is Q_j^i, which can be computed by a recursive method. It follows that:

$$Q_j^i = \begin{cases} 0, & i = 0 \\ dq_0, & i = 1 \\ \max\left\{\min\left\{Q_j^{i-2}, 2 \cdot cq_{i-1}\right\}, \min\left\{Q_j^{i-1}, dq_{i-1}\right\}\right\}, & 2 \leq i \leq m \end{cases} \tag{20}$$

We explain Eq. (20) in details. Consider the wireless communication from node $v_{j_{i-1}}$ to node $v_{j_{i+1}}$. Under the direct transmission scheme, the achievable rates of two links $l\left(v_{j_{i-1}}, v_{j_i}\right)$ and $l\left(v_{j_i}, v_{j_{i+1}}\right)$ should both exceed the threshold Q_j so as to satisfy the requirement. Then, the traffic amount from node $v_{j_{i-1}}$ to node $v_{j_{i+1}}$ is at least Q_j during two time slots. Under the cooperative scheme, node $v_{j_{i-1}}$ communicates with node $v_{j_{i+1}}$ in two time slots. Therefore, node $v_{j_{i-1}}$ should transmit the traffic Q_j at least to node $v_{j_{i+1}}$ in two time slots. In other words, the minimum rate from $v_{j_{i-1}}$ to $v_{j_{i+1}}$ with relay v_{j_i} should be $\frac{Q_j}{2}$ at least. As a result, there is a factor 2 in front of variable cq_{i-1} in Eq. (20).

By Eq. (20), the RLC method obtains the achievable rate Q_j^m of path Ψ_j under lifetime constraint, denoted by

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BS-RRP Algorithm:
Step 1: Algorithm Initialization
$L_{\min} = 0$;  $L_{\max} = 10^6$;
finished = true;
Step 2: Relay Assignment and Rate-Power Allocation
While (finished) do
$L_{mid} = \frac{L_{\min} + L_{\max}}{2}$
If $\frac{L_{max} - L_{min}}{L_{max}} < \varepsilon$
  Then finished = false
      $L_{mid} = L_{\min}$
      Algorithm terminate;
$Q_{total} = 0$
For each path $\Psi_i$
  $Q_{total} = Q_{total} + RLC(\Psi_i, L_{mid})$
If $Q_{total} < Q$
  Then $L_{\max} = L_{mid}$
  Else $L_{\min} = L_{mid}$
Return $L_{mid}$
```

Fig. 2 Formal description of the BS-RRP algorithm

$Q_j^{\max}$. For implementation of relay assignment, we add a boolean variable vector, state. Initially, each variable is set to false. From Eq. (20), if $Q_j^i = \min\left\{Q_j^{i-2}, 2 \cdot cq_{i-1}\right\}$, state[$i$] is set as true. Then, we check each node from $v_{j_{m-1}}$ to v_{j_1} whether it should be selected for cooperative communication or not. The procedure is as follows: if Q_j^i is not less than $Q_j^{\max}$ and state[i] is true, node $v_{j_{i-1}}$ is designated as a cooperative relay. Accordingly, the cooperative relay assignment has been fulfilled on each path. The RLC sub-routine is formally described in Fig. 3.

4.2 Performance analysis

This section analyzes the performance of the BS-RRP algorithm. We first prove the optimality of the RLC sub-routine.

Lemma 1 *RLC will determine the maximum achievable rate under lifetime constraint for a given path.*

Proof Given lifetime constraint L, transmission power of each node v should not exceed $\frac{E_v}{L}$. For a path $\Psi_j = v_{j_0}(s)v_{j_1}\ldots v_{j_{m-1}}v_{j_m}(d)$, we prove the lemma by induction. For $i = 1$, we consider the sub-path $\Psi_j^1 = v_{j_0}(s)v_{j_1}$. Obviously, its achievable rate is dq_0, shown in Eq. (20). Assume that the RLC sub-routine can obtain the maximum rates for sub-paths $\Psi_j^1, \ldots, \Psi_j^i$, denoted by $Q_j^1, \ldots, Q_j^i$. Now, we compute the maximum achievable rate of sub-path Ψ_j^{i+1}. For node v_{j_i}, there are two cases to be discussed. If node v_{j_i} is designated as a cooperative relay, the rate of this sub-path is $\min\left\{Q_j^{i-2}, 2 \cdot cq_{i-1}\right\}$. However, if node v_{j_i} is a traditional relay, the rate of this sub-path is $\min\left\{Q_j^{i-1}, dq_{i-1}\right\}$. So, the achievable rate of sub-path Ψ_j^{i+1} can be expressed as $\max\left\{\min\left\{Q_i^{i-1}, 2 \cdot cq_i\right\}, \min\left\{Q_j^i, dq_i\right\}\right\}$. As a result, we conclude that the *RLC* sub-routine can compute the maximum achievable rate for path Ψ_j. The lemma is proved. □

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Sub-routine RLC($\Psi_j, L$):
For $i$=1 to $m$ do
  state[$i$]=false;
  Compute the transmission power of node $v_{j_i}$ as $p_{v_{j_i}} = \frac{E_{v_{j_i}}}{L}$
  Compute two variable $cq_i$ and $dq_i$ for node $v_{j_i}$;
  $Q_j^i = \begin{cases} 0 & ,i=0 \\ dq_0 & ,i=1 \\ \max\{\min\{Q_j^{i-2}, 2 \cdot cq_{i-1}\}, \min\{Q_j^{i-1}, dq_{i-1}\}\} & ,2 \le i \le m \end{cases}$
  If $Q_j^i = \min\{Q_j^{i-2}, 2 \cdot cq_{i-1}\}$
    Then state[$i$]=true;
$Q_j^{\max} = Q_j^m$;
For each node $v_{j_i}$ from node $v_{j_{m-1}}$ to node $v_{j_1}$
  If $Q_j^i \ge Q_j^{\max}$ and state[$i$]=true
  Then node $v_{j_{i-1}}$ is selected as a cooperative relay;
return $Q_j^{\max}$
```

Fig. 3 Formal description of sub-routine RLC

Followed by Lemma 1, we analyze the approximate performance of the BS-RRP algorithm.

Theorem 2 *BS-RRP can reach the approximate performance of* $1 - \varepsilon$, *where* ε *is an arbitrarily small positive constant.*

Proof Without loss of generality, assume that the optimal lifetime of multiple paths is L_{opt} by joint relay assignment and rate–power allocation. We consider the final snapshot of $L_{\min}$, L_{mid} and $L_{\max}$ before algorithm termination. According to the algorithm, $L_{\min} \le L_{mid} \le L_{\max}$. Obviously, the optimal lifetime L_{opt} must belong to the interval [$L_{\min}$, $L_{\max}$]. That is, $L_{\min} \le L_{mid} \le L_{\max}$. The algorithm terminates if $\frac{L_{\max} - L_{\min}}{L_{\max}} < \varepsilon$. Thus, the approximate factor is:

$$\frac{L_{mid}}{L_{opt}} \ge \frac{L_{\min}}{L_{\max}} = 1 - \frac{L_{\max} - L_{\min}}{L_{\max}} > 1 - \varepsilon.$$

□

Next, we analyze the time complexity of RLC. For a given path Ψ_j, this method will check all nodes on the path twice for rate allocation and relay assignment respectively. The time complexity is $O\left(\left|\Psi_j\right|\right)$, where $\left|\Psi_j\right|$ is the number of nodes on path Ψ_j. Now, we compute the time complexity of the BS-RRP algorithm. Assume that n is the number of nodes in the network. The first step mainly fulfills the algorithm initialization, and the time complexity is $O(1)$. In the second step, the algorithm initializes two variables for each node, which takes the time complexity of $O(n)$. Then, BS-RRP lasts for totally $\log \frac{1}{\varepsilon}$ rounds for rate allocation. In each iteration, the algorithm will execute the RLC sub-routine on all paths. Thus, the time complexity of each round is $O(n)$. Thus, the total time complexity of BS-RRP is $O(1) + O(n) + O\left(n \log \frac{1}{\varepsilon}\right) = O\left(n \log \frac{1}{\varepsilon}\right)$.

5 Algorithm for the link-disjoint multi-path case

5.1 Algorithm description

For the link-disjoint multi-path case, one node may belong to several paths from source to destination, which increases the difficulty of resource allocation among all nodes. As problem formulization belongs to a non-linear program, this section proposes a pattern-search-based algorithm for joint relay assignment and rate–power allocation (called

PS-RRP). The algorithm mainly consists of two steps: algorithm initialization and resource allocation.

5.1.1 Description of algorithm initialization

In the first step, the algorithm will select a rough solution for the LRRP problem. Initially, each path is allocated a rate Q, and the rate allocation pattern for path set $\Re$ is $X_1 = (Q,\ Q,\ldots,\ Q)^T$. For simple description, the jth dimension of the rate pattern X is denoted by X^j, which is the allocated rate for path Ψ_j. The aggregate rate Q_{total} of multiple paths is the total rates of the path set $\Re$. That is, $Q_{total} = k \cdot Q$, where k is the number of paths. As $k \geq 1$, this solution satisfies the rate requirement. After each node computes its power consumption on the path, we can determine the maximum lifetime of path set $\Re$, denoted by $f(X_1)$, under rate allocation pattern X_1. In the following, the variable L_c denotes the current network lifetime, and is updated with algorithm execution.

Next, we design a sub-routine to compute the maximum lifetime of each path under rate constraint. As relay assignment affects the network lifetime, we propose a lifetime-aware relay assignment method, called LBR, to fulfill this task. This method mainly uses the dynamic program mechanism for joint relay assignment and power allocation on each path Ψ_j to provide the required rate Q_j. Initially, the transmission power of each node is 0. While the algorithm processes path $\Psi_j = v_{j_0}(s)v_{j_1}\ldots v_{j_{m-1}}v_{j_m}(d)$, we assume that all nodes on other paths have been assigned the powers. For each node $v_{j_i} \in \Psi_j$, it may act as a cooperative relay or a traditional relay for wireless transmission. We compute the traditional and cooperative lifetimes of this node corresponding to traditional and cooperative communication schemes. As node v_{j_i} directly transmits to node $v_{j_{i+1}}$, power consumption is computed in Eq. (14) and its traditional lifetime η_i can be derived by Eq. (18). While node v_{j_i} acts as a cooperative relay from node $v_{j_{i-1}}$ to node $v_{j_{i+1}}$, power allocation among nodes $v_{j_{i-1}}$ and v_{j_i} is derived by Eqs. (9, 10, 12). Note that, the cooperative lifetime ρ_i is the minimum lifetime of nodes $v_{j_{i-1}}$ and v_{j_i}, and can also be derived by Eq. (18). Let Ψ_j^i be the sub-path from node v_{j_0} to node v_{j_i} on path Ψ_j. The maximum lifetime L_j^i of sub-path Ψ_j^{i-2} can be calculated by the recursive way. Assume that we have obtained the lifetimes L_j^{i-2} and L_j^{i-1} of sub-paths Ψ_j^{i-2} and Ψ_j^{i-1} under rate constraint. There are two cases of lifetime L_j^i. One is that node $v_{j_{i-1}}$ directly transmits to node v_{j_i}. The lifetime of sub-path Ψ_j^i is $\min\left\{L_j^{i-1}, \eta_{i-1}\right\}$. The other is that node $v_{j_{i-1}}$ acts as a cooperative relay from nodes $v_{j_{i-2}}$ to v_{j_i}. So, the lifetime of sub-path Ψ_j^i is described as $\min\left\{L_j^{i-2}, \rho_{i-1}\right\}$. As a result, it follows:

$$L_j^i = \begin{cases} \infty, & i = 0 \\ \eta_0, & i = 1 \\ \max\left\{\min\left\{L_j^{i-2}, \rho_{i-1}\right\}, \min\left\{L_j^{i-1}, \eta_{i-1}\right\}\right\}, & 2 \leq i \leq m \end{cases} \tag{21}$$

In this way, the algorithm obtains the maximum lifetime of path Ψ_j under rate constraint, denoted by L_j^m or $L_j^{\max}$. For relay assignment, we add a boolean variable vector, state. Initially, each variable is false. By Eq. (21), if $L_j^i = \min\left\{L_j^{i-2}, \rho_{i-1}\right\}$, state[$i$] is set as true. Then, we check each node from $v_{j_{m-1}}$ to v_{j_i} whether it can be selected for cooperative communication or not. The procedure is as follows: if L_j^i is not less than $L_j^{\max}$ and state[i] is true, node $v_{j_{i-1}}$ is designated as a cooperative relay. Note that, if $L_j^i < L_j^{\max}$, it means the lifetime of sub-path Ψ_j^i is less than $L_j^{\max}$. Since Ψ_j^i is a sub-path of Ψ_j, the lifetime of this path Ψ_j can not reach $L_j^{\max}$ either. Thus, we need to test for $L_j^i \geq L_j^{\max}$ to select a node as a cooperative relay. The LBR method is given in Fig. 4. After executing the LBR method on all paths one-by-one, each path is allocated a uniform rate (i.e., Q), and all nodes have computed power consumptions on multiple paths.

5.2 Description of resource allocation

In the second step, we adjust the resource allocation for all nodes on the multiple paths so as to prolong the network lifetime under the rate requirement. This step mainly consists of an iterative procedure. Assume that there is a rough rate allocation solution, denoted by $T_{1,0}$. Initially, $T_{1,0} = X_1$. In each iteration, we select a step-size $\delta(>0)$ for rate adjustment. In the algorithm, $\delta = \frac{k-1}{ck}Q$, where k is the number of paths and c is a constant, such as $c = 20$. For uniform description, we denote $\Delta_i = (0,\ldots,\ \delta,\ldots,\ 0)^T$, in which the ith dimension is δ. The algorithm determines the

```
Sub-routine LBR($\Psi_j$, $Q_j$):
For $i$=1 to $m$ do
 state[$i$]=false;
 Compute variables $\eta_i$ and $\rho_i$;
 Compute $L_j^i$ by equation (21)
  If $L_j^i = \min\{L_j^{i-2}, \rho_{i-1}\}$
     Then state[$i$]=true;
$L_j^{\max} = L_j^m$;
For each node $v_{j_i}$ from node $v_{j_{m-1}}$ to node $v_{j_1}$
   If $L_j^i \geq L_j^{\max}$ and state[i]=true
    Then node $v_{j_{i-1}}$ is selected as a cooperative relay;
return $L_j^{\max}$
```

Fig. 4 Formal description of sub-routine *LBR*

Fig. 5 Formal description of the PS-RRP algorithm

```
PS-RRP Algorithm:
Step 1: Algorithm Initialization
    $X_1 = (Q, ..., Q)^T$
    for $j = 1$ to $k$ do
        $LBR(\Psi_j, Q)$ //power allocation and relay assignment
Step 2: Resource Allocation
    $\delta = \frac{k-1}{ck}Q$
    $cycle = true$
    $T_{1,0} = X_1$
    $i = 1$
    while($cycle$) {
        $Q_{total} = \sum_{j=1}^{k} T_{i,0}^{j}$    // current aggregate rate
        $better = false$
        for $j = 1$ to $k${
            if ($Q_{total} - \delta > Q$ && $LBR(\Psi_j, T_{i,j-1}^{j} - \delta) > \mathcal{L}_c$){
                $T_{i,j} = T_{i,j-1} - \Delta_j$  //$\Delta_j = (0, ..., \delta, ...0)^T$
                $better = true$
                $Q_{total} = Q_{total} - \delta$
            }
            else $T_{i,j} = T_{i,j-1}$
        } //end for
        If ($better$)// Find a better rate pattern
            $X_{i+1} = T_{i,k}$
            $T_{i+1,0} = 2X_{i+1} - X_i$
            $i = i + 1$
        else //i.e., better = false
        If ($f(T_{i,0}) < f(X_i)$)
            $T_{i,0} = X_i$
        else{
            if ($\delta \leq \theta$) // $\theta$ represents a small constant
                $cycle = false$
                else $\delta = \frac{\delta}{c}$    //shorten the step-size
            $X_{i+1} = T_{i,0}$
            $T_{i+1,0} = X_{i+1}$
            $i = i + 1$
        } //end else
}//end while
```

next pattern by lifetime detection on each path. For path Ψ_1, if network lifetime can be improved and rate requirement is stilled satisfied as path Ψ_1 is allocated a rate $X_i^1 - \delta, T_{i,0} - \Delta_1$ is selected as the temporary pattern, denoted by $T_{i,1}$. Note that, we can use the LBR method to implement the lifetime detection, i.e., $LBR\left(\Psi_1, X_i^1 - \delta\right)$. Assume that we have obtained the rate allocation pattern $T_{i,j}$, and updated the variables L_c and Q_{total}. The new pattern is computed as follows: if $Q_{total} - \delta \geq Q$ and $LBR\left(\Psi_{j+1}, T_{i,j}^{j+1} - \delta\right) > L_c$, it means that a new rate allocation pattern with better lifetime has been detected on path Ψ_{j+1}. That is, $T_{i,j+1} = T_{i,j} - \Delta_{j+1}$. Otherwise, $T_{i,j+1} = T_{i,j}$. In this way, we obtain the rate allocation pattern $T_{i,k}$.

There are two cases of rate pattern $T_{i,k}$. On the one hand, a new rate allocation pattern $T_{i,k}$ is found by the above processing. That is, $T_{i,k} \neq T_{i,0}$. The algorithm generates another rate pattern as $X_{i+1} = T_{i,k}$, $T_{i+1,0} = 2X_{i+1} - X_i$, and continues to a new search from the pattern $T_{i+1,0}$. On the other hand, there is no pattern with improved network lifetime by detection on any paths. The algorithm will compare the network lifetimes of two rate allocation patterns $T_{i,0}$ and X_i, denoted by $f(T_{i,0})$ and $f(X_i)$. The maximum lifetime of multiple paths can be computed by repeatedly running the LBR method on the path set $\Re$. If $f(T_{i,0}) < f(X_i)$, we set $T_{i,0} = X_i$, and the algorithm searches a better solution around the pattern $T_{i,0}$ again. Otherwise, we can not find a new rate pattern with better network lifetime under the current step size. So, the algorithm shortens the step size by setting $\delta = \frac{\delta}{c}$, and continues to search the solution around the rate pattern $T_{i+1,0}$. That is, $T_{i+1,0} = X_{i+1} = T_{i,0}$. The algorithm terminates if the current step-size δ is less than a given threshold θ, where θ is a small positive constant. The integrated PS-RRP algorithm is formally described in Fig. 5.

5.3 Performance analysis

Theorem 3 *The PS-RRP algorithm will terminate in finite iterations.*

Proof There are two cases at the end of each iteration in the second step. Assume that the algorithm can find a better rate allocation pattern in the iteration. Therefore, the algorithm moves a step size δ to the optimal pattern at least. If no better rate pattern is found at the end of this iteration, the algorithm will find a better solution in the iteration from a new start pattern. As a result, the algorithm moves a step size to a better rate allocation pattern through two iterations at most. Therefore, the algorithm will execute at most $2 \cdot \frac{(k-1)Q}{\delta} = 2 \cdot \frac{(k-1)Q}{\frac{(k-1)Q}{ck}} = 2kc$ rounds. When no better solution is found, the algorithm shortens the step size by $\delta = \frac{\delta}{c}$. Then, for a certain step size, the algorithm will run $2kc$ iterations at most, for the rate on each path will be reduced less than $c \cdot \delta$. As the algorithm will terminate until the current step size is not more than θ, it deals with totally $\log_c \frac{Q}{\theta}$ types of step sizes. As a result, the algorithm will run $2kc \log_c \frac{Q}{\theta}$ iterations at most. □

Next, we compute the time complexity of LBR. For a given path Ψ_j, this method will check all nodes in the path twice for lifetime determination and relay assignment. The time complexity is $O(|\Psi_j|)$, where $|\Psi_j|$ is the number of nodes on path Ψ_j. Now, we analyze the time complexity of the PS-RRP algorithm. Assume that n is the number of nodes in the network. The first step mainly fulfills the algorithm initialization. The time complexity is $O(kn)$. In the second step, the algorithm will consist of totally $2kc \log_c \frac{Q}{\theta}$ iterations. In each iteration, the algorithm will detect the network lifetime on all paths, which costs the time complexity of $O(kn)$. As a result, the total time complexity is $O(kn) + O(kn) \times 2kc \log_c \frac{Q}{\theta} = O(k^2 cn \log_c \frac{Q}{\theta}) = O(k^2 n \log_c \frac{Q}{\theta})$, where c is a predefined constant.

6 Numerical results

6.1 Simulation setting

This section describes the numerical results to demonstrate the high efficiency of the BS-RRP and PS-RRP algorithms. However, there are no special works about relay assignment and rate–power allocation for multiple paths, and some works [4, 6, 7] all assume that the transmission rate of each link or transmission power of each node are fixed. Though there are some references that deal with one path and/or one hop only, they can not be extended to the multi-hop and multi-path case directly. Therefore, we will adopt three related algorithms about rate and power allocation as references for performance comparison. The first one is called as the URA algorithm, which implements the uniform rate allocation among multiple paths under the traditional communication scheme. That is, each path will be allocated a rate $\frac{Q}{k}$, where Q is the required rate and k is the number of paths from source to destination. After each node determines its power consumption on every path, the network lifetime is also derived. The time complexity of the URA algorithm is $O(n)$, where n is the number of nodes in a network. The second one, called BS-RP, uses the binary search method for rate and power allocation among the node-disjoint multi-path routes under the traditional communication scheme. Similar to the BS-RRP algorithm, the time complexity of BS-RP is $O(n \log \frac{1}{\varepsilon})$ too, where ε is an arbitrarily small value. The third one (called PS-RP), in which cooperative communication (or relay assignment) is not permitted, is the simplified version of the PS-RRP algorithm. As the time complexity of power allocation under the direct transmission and cooperative communication are the same as introduced in Sect. 3.2, the time complexity of the PS-RP algorithm is $O(k^2 cn \log_c \frac{Q}{\theta})$, where c and θ are pre-defined constants. The BS-RRP algorithm will be compared with the URA and BS-RP algorithms, while the PS-RRP algorithm will be compared with the URA and PS-RP algorithms to show the lifetime efficiency with cooperative communication. In the following, we introduce the simulation set-up and performance measurement.

By default, the simulations setup a wireless network with 120 nodes in the square area 800 m × 800 m randomly. By assumption, we consider two disjoint paths from a source to a destination, which can be constructed by the Suurballe algorithm [3]. The default rate requirement between two nodes is 8 Mbps. In the network, all nodes except the source and destination nodes can potentially act as cooperative relays. To compute the link rate, we use the same parameters as those in the simulations [11]. The bandwidth for each channel is $W = 22$ MHZ. For simplicity, we assume that the parameter h_{sd} only includes the path loss component between nodes s and d is given by $h_{sd}^2 = |sd|^{-4}$, where $|sd|$ is the distance (in meters) between two nodes. For the *AWGN* channel, we regard that the variance of noise is $10^{-10}W$ at all nodes. In the simulations, each cooperative relay works on the *DF* mode.

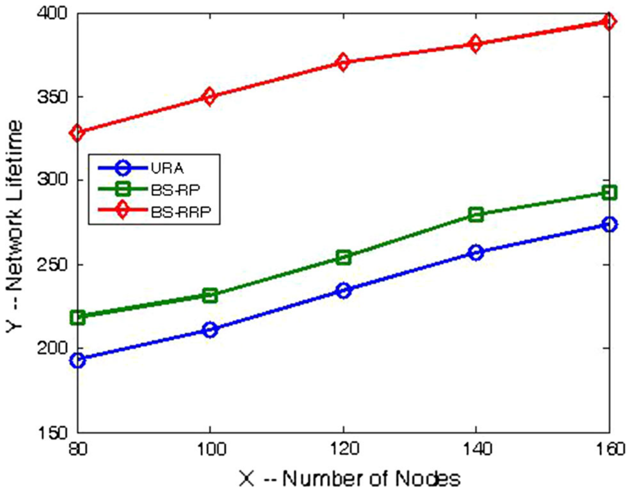

Fig. 6 Number of nodes versus network lifetime for the node-disjoint case

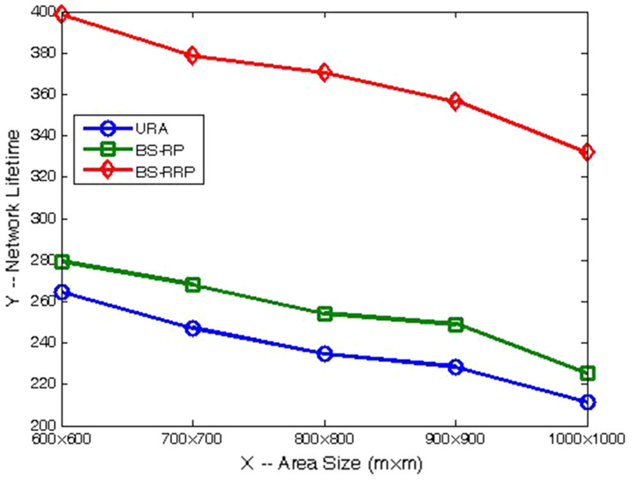

Fig. 7 Area size versus network lifetime for the node-disjoint case

For performance comparison, we use the network lifetime, which is the minimum lifetime of all nodes on multiple paths defined in Eq. (19), as the main performance metric. We mainly observe the impact of different network parameters on the lifetime of multiple paths according to the node-disjoint and link-disjoint cases. In each simulation, we run these algorithms on 100 random topologies, and the plotted results are averaged over random topologies.

6.2 Simulation results for different algorithms

In the first group of simulations, we compare BS-RRP with the URA and BS-RP algorithms for the node-disjoint case. The first experiment shows the impact of the number of nodes on the network lifetime of multi-path routing. Except the default setting, we change the number of nodes from 80 to 160. The simulation result shows that the network lifetime will be improved as the number of nodes increases. The reason is that, in the denser network, the average distance between two nodes becomes shorter, which also leads to the power saving. From Fig. 6, we conclude that the BS-RRP algorithm can prolong the network lifetimes about 36.14 and 30.22 % compared with the URA and BS-RP methods.

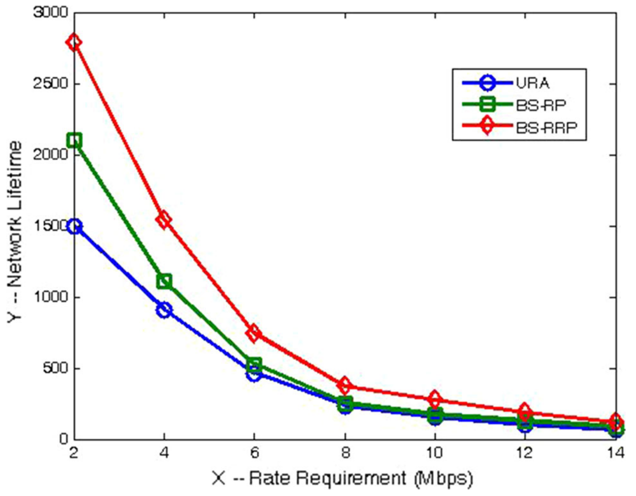

Fig. 8 Rate requirements versus network lifetime for the node-disjoint case

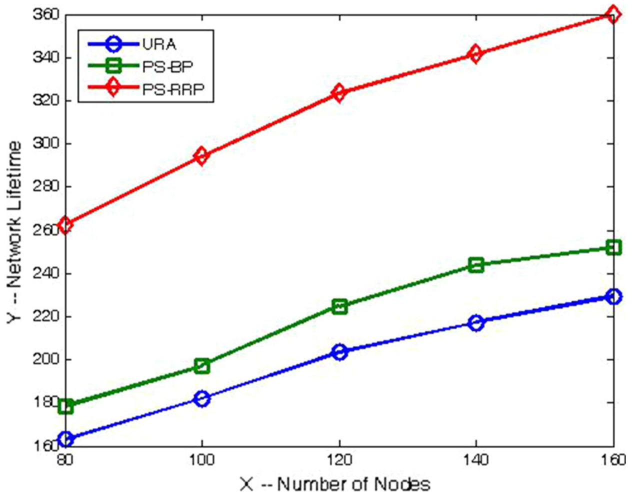

Fig. 9 Number of nodes versus network lifetime for the link-disjoint case

The second experiment shows the impact of area size on the network lifetime of multi-path routing. In the simulation setting, the area size is varied from 600 m × 600 m to 1000 m × 1000 m gradually. The simulation result is illustrated in Fig. 7. As area size is becoming wider, the

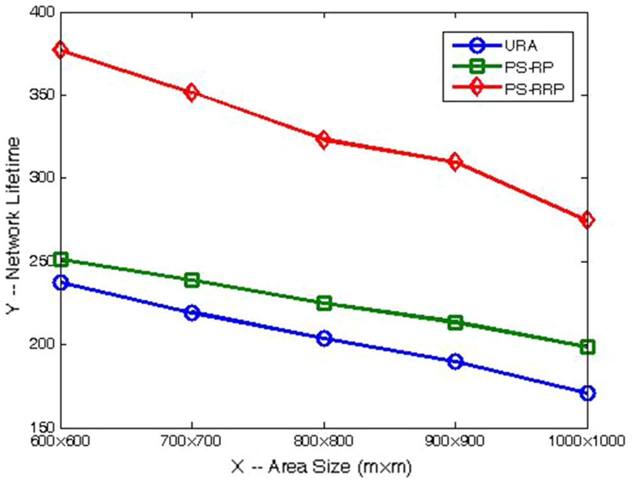

Fig. 10 Area size versus network lifetime for the link-disjoint case

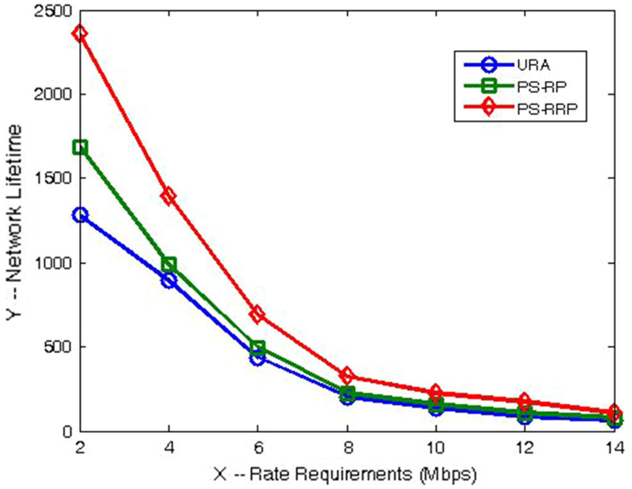

Fig. 11 Rate requirements versus network lifetime for the link-disjoint case

average distance between two nodes also becomes larger, which leads to much more power consumption and shortened network lifetime. From Fig. 7, we observe that BS-RRP will prolong the network lifetimes about 32.82 and 25.32 % compared with the URA and BS-RP methods.

The third experiment shows the network lifetime by varying the rate requirements between source and destination. The required rate is changed from 2 to 14 Mbps. With the increase of the rate requirement, the assigned power on each node will be increased accordingly, and the network lifetime is shortened significantly. From Fig. 8, the BS-RRP algorithm prolongs the network lifetimes about 30.87 and 21.67 % compared with the URA and BS-RP methods, respectively.

In the second group of simulations, we mainly compare PS-RRP with the URA and PS-RP algorithms for link-disjoint multi-path routing. The first experiment shows the impact of the number of nodes on the network lifetime. We change the number of nodes from 80 to 160. As the number of nodes increases, the average distance between two nodes becomes shorter, and the average power consumption is also decreased. From Fig. 9, we know that the PS-RRP algorithm prolongs the network lifetimes about 37.12 and 30.78 % compared with the URA and PS-RP methods, respectively.

The second experiment shows the impact of area size on the network lifetime of link-disjoint multi-path routing. The area size is varied from 600 m × 600 m to 1000 m × 1000 m gradually. The simulation result shows that the network lifetime will be decreased as the area size is becoming wider. The reason is that, each node will averagely cost much more power consumption for wireless transmission under the larger area size. From Fig. 10, we observe that PS-RRP can prolong the network lifetimes about 37.63 and 30.94 % compared with the URA and PS-RP methods.

The third experiment shows the impact of the rate requirements on the network lifetime. The required rate between the source node and the destination node is changed from 2 Mbps to14 Mbps. With the increase of the rate requirement, the network lifetime is shortened significantly. From Fig. 11, we can conclude that the PS-RRP algorithm can prolong the network lifetimes about 41.34 and 30.44 % compared with the URA and PS-RP methods, respectively.

7 Conclusions

This paper mainly studies the joint relay assignment and rate–power allocation for multi-path routing to prolong the network lifetime by exploring the advantages of cooperative communications. We present the BS-RRP and PS-RRP algorithms for the node-disjoint and link-disjoint cases respectively. Two algorithms adopt the binary-search method and pattern-search method to implement the joint multi-resource allocation for multi-path routings. The simulation results show that the two algorithms can improve the network lifetimes compared with the traditional resource allocation methods in many situations. Parallel transmission is an efficient way to achieve the aggregate throughput. However, this work assumes that there is no interference among parallel transmissions. Thus, we will consider the interference-aware resource allocation problem in the future.

Acknowledgments The work by Hongli Xu, Liusheng Huang, and Long Chen is supported by National Science and Technology Major Project under Grant No. 2012ZX03005009, the National Science Foundation of China under Grant Nos. U1301256, 61272133, 61170058, 51274202, and 61472383, Special Project on IoT of China

NDRC (2012-2766), the NSF of Jiangsu Province No. BK2012632, the NSF of Anhui Province No. 1408085MKL08, Jiangsu industry-university-research Fund No. BY2012127, and Suzhou Industry Fund No. SYG201302. The work by Shan Lin is supported by CNS-1239108, IIS-1231680, CNS-1218718.

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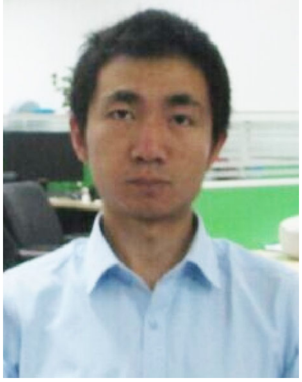

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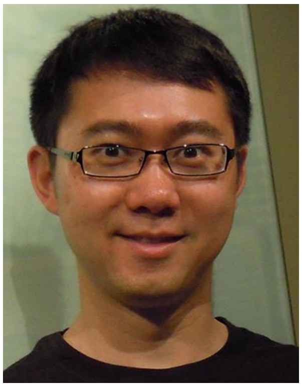

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