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Research Article

QoS-Aware Maximally Disjoint Routing in Power-Controlled Multihop CDMA Wireless Ad Hoc Networks

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A joint power control and maximally disjoint routing algorithm is proposed for multihop CDMA wireless ad hoc networks. A framework of power control with QoS constraints in CDMA wireless ad hoc networks is introduced and the feasibility condition of the power control problem is identified. Both centralized solution and distributed implementations are derived to calculate the transmission power given the required throughput and the set of transmitting nodes. Then, a joint power control and maximally disjoint routing scheme is proposed for routing data traffic with minimum rate constraint while maintaining high energy efficiency and prolonged network lifetime. Furthermore, in order to provide reliable end-to-end data delivery, the proposed joint power control and maximally disjoint routing scheme is augmented by a dynamic traffic switching mechanism to mitigate the effect of node mobility or node failure. Simulation results demonstrate the effectiveness of the proposed scheme.

1. INTRODUCTION

Wireless ad hoc networks have come under extensive scrutiny in terms of research focus, due to their ability to provide wireless networking capability in scenarios where either no fixed wired infrastructure is available or rapid implementation is possible (e.g., disaster relief efforts, battlefields, etc.). However, the lack of fixed infrastructure introduces great design challenges, including protocols design for routing, medium access control (MAC), and mobility management. Although these protocols may function at different layers, it is now agreed that jointly designed protocols across layers will improve the network performances. In addition, energy efficiency and quality-of-service (QoS) support also need to be taken into consideration. In this paper, we study joint power control and routing for QoS support in CDMA wireless ad hoc networks.

In a wireless ad hoc network architecture, MAC protocol plays a critical role in optimizing bandwidth efficiency and resolving collisions due to the broadcast nature of wireless channels. In most standardized wireless ad hoc networks, such as in the widely deployed IEEE 802.11x networks, only one user is allowed to transmit at an instance of time. It is demonstrated in [1] that, compared to the distributed coordination function (DCF) mode of the IEEE 802.11x networks, CDMA-based MAC protocols achieve a significant increase in network throughput at no additional cost in energy consumption. Hence, CDMA is employed as the MAC scheme for multihop wireless ad hoc networks (considered in this paper), where multiple concurrent transmissions are allowed.

Power control is applied in a wireless ad hoc network to control transmission range and to keep the network fully connected [2]. Because CDMA systems are interference limited, power control also serves as a tool for interference management in CDMA wireless networks to guarantee the success of multiple concurrent transmissions. Because the transmission power of each node will decide the number of nodes in its transmission range, power control will affect the topology of a wireless ad hoc network. Thus, routing needs to be considered jointly with power control. Furthermore, using the minimum required transmission power-related routing metric, energy-efficient paths can be calculated.

In a wireless ad hoc network, QoS support is desirable by many applications. However, as pointed out in previous research [3, 4], “hard QoS” is very difficult to support in wireless ad hoc networks because of node mobility, lack of central control, and the constantly changing wireless channels. However, many applications do not require “hard QoS” and accept “soft QoS.” For example, many multimedia applications accept "soft QoS" and use rate adaptive schemes to mitigate disruptions [5]. Hence, only "soft QoS" is supported in this paper.

QoS is a measure of performance level of a service offered by the network to the user. QoS requirements include minimum data rate, maximum delay, maximum delay jitter, and maximum packet loss rate. A guarantee on minimum data rate is arguably the simplest possible QoS guarantee. Therefore, we believe it is natural that mobile users would expect such an assurance. For example, video can become unusable if the data rate is too low. Even for static TCP-based applications such as web browsing, if the data rate is too low, then we typically get a large queue buildup which can lead to TCP timeouts and poor performance. Such effects were discussed by Chakravorty et al. in [6]. Providing a minimum rate guarantee can also help to smooth out the effects of a variable wireless channel. Furthermore, by setting minimum data rate differently for different users we can ensure service differentiation.

1.1. Design goals and paper contributions

One of the fundamental challenges in wireless ad hoc network routing is how to provide end-to-end QoS support while maintaining low energy consumption and long network lifetime. In addition, node mobility and node failures introduce challenges for reliable data delivery. In this study, we propose a design that addresses *all* the above requirements. Both energy efficiency and QoS support (minimum rate) are considered when we jointly design power control and routing. Also, in order to provide assured QoS, we propose multiple disjoint paths (minimum two) routing as opposed to single path routing. Single path routing is not reliable. The path may be broken during data transmission because of node mobility or node failure. Rerouting after detection of a broken path may incur too much extra delay in data delivery and cause loss of information. The proposed power-aware maximally disjoint routing scheme to calculate two "energy-efficient maximally disjoint paths" for each data flow provides the QoS assurance for end-user applications. One path acts as the primary path for sending data traffic and the other acts as a backup path and is stored in the routing table of the sender. In case the primary path fails, the traffic will be switched to a designated backup path. The sender will monitor both paths and follow the route maintenance in standard MANET routing protocols, such as that in DSR [7].

Outline of the proposed scheme

Given the current existing end-to-end traffic sessions and channel allocations across the network, the procedures of the proposed scheme are as follows.

(1) Determine the power-controlled connectivity graph by performing perchannel-based power control. This step will find all the feasible links that are able to accommodate the coming traffic with specified QoS in terms of minimum data rate. A detailed explanation and an example are given in Section 3.

(2) Perform balanced energy-split multipath routing iteratively to find a primary path and the associated maximally disjoint backup path.

(3) Send traffic only along the primary path and monitor both the primary path and the backup path for available bandwidth. If the primary path is broken, switch the traffic to the backup path.

Main contributions

The main contributions of this study include the following.

(1) Joint power control and maximally disjoint multipath routing is proposed using the realistic interference model in this study rather than the simplified interference model in [8], where interference is not considered at all. In fact, the joint power control and multipath routing problem is a much tougher problem to be solved when interference is taken into account. Our paper addresses this issue and this is unique in our paper.

(2) Our paper proposed the perchannel-based power control, which provides a correct solution in a multihop network where only cochannel interference should be managed by power control and we do not assume that all the links are interferers to each other as has been assumed in another study [9]. Thus, our proposed design has a substantial gain (more than 300%) in terms of the capabilities of accommodating data traffic over the previous study [9] which only provided a lower bound.

(3) Our paper proposed the balanced BESMR as opposed to SMR in [10]. It is shown that the BESMR achieves a significant gain (more than 140%) in terms of network lifetime as compared to that of SMR technique in [10].

(4) Data is only sent along the primary path rather than being sent simultaneously along all the multiple paths, thus achieving high bandwidth efficiency.

(5) An end-to-end traffic monitoring and switching mechanism is proposed to provide reliability against node mobility and link failures. The disturbance and delay are minimized when primary path is broken. In addition, the proposed end-to-end mechanism simplifies implementation because only the source and the destination nodes are involved.

Detailed comparison of our proposed approach with the current approaches in the literature are provided in Section 2.

The rest of the paper is organized as follows: Section 2 describes related work. Section 3 introduces the power control framework and the power-controlled connectivity model with minimum rate guarantee for CDMA wireless ad hoc networks. An iterative joint power control and maximally disjoint routing algorithm that may employ different energy-related routing metrics is proposed in Section 4. The dynamic path restoration for guaranteed data delivery is proposed in Section 5. Performance evaluations are carried out through extensive discrete event simulations, and the simulation results are given in Section 6. Section 7 contains the concluding remarks.

2. RELATED WORK

Multipath routing techniques have been proposed for wireless ad hoc networks in many previous studies. Lee and Gerla [11] proposed AODV-BR, where alternate routes are maintained locally along the "backbone" of the primary path and utilized when the primary path fails. Other proposals include TORA [12] and AOMDV [13]. However, disjoint paths and QoS support are not considered in the above works.

Power-aware maximally disjoint routing has been considered by Srinivas and Modiano [8]. It allows the data to be sent to multiple disjoint paths *simultaneously* to achieve diversity. This was not intended to handle route disruptions. It used the simplified interference model where the transmission power is proportional to the link distance only ($p_{ij} = d_{ij}^{\alpha}$ and $2 \le \alpha \le 4$). No required throughput is considered. Because there are major differences on how to use the obtained disjoint paths to send data between our approach and that in [8], the routing designs are completely different. Moreover, our scheme is augmented by a dynamic traffic switching mechanism to deal with node mobility or node failure.

Another related work has been done in terms of QoS provisioning [9]. Iterations of power control and routing have been proposed to perform QoS provisioning for CDMA wireless ad hoc networks. The results are routes for every node pair in the network. However, finding disjoint paths between every node pair while achieving minimum energy may needlessly minimize energy usage over nodes that may not even be transmitting, and yields suboptimal solutions for nodes that indeed are transmitting. Disjoint paths are not considered in that work.

3. POWER CONTROL FRAMEWORK AND POWER-CONTROLLED CONNECTIVITY

The topology and connectivity of a wired network are easy to determine because there exists a communication link between two nodes whenever there is a physical link between them. However, this is not the case in CDMA wireless ad hoc networks. Whether there is a communication link between two nodes or not depends on many physical layer parameters, such as the transmission power, spreading gain, modulation, and coding scheme. As a result, we define *power-controlled connectivity* in CDMA wireless ad hoc networks as follows.

Definition 1. Given the spreading gain, modulation and coding scheme, and the desired throughput, a link between two nodes exists when the corresponding target signal-to-interference ratio (SIR) is achievable. In other words, the transmission power to achieve the target SIR is below the maximum allowable transmission power.

Definition 2. The power-controlled connectivity graph includes the feasible set of links (and the associated nodes) that may accommodate the traffic flow with the desired data rate, R^{tar}. In order to obtain the power-controlled connectivity graph given R^{tar}, a power control framework for CDMA wireless ad hoc networks is introduced.

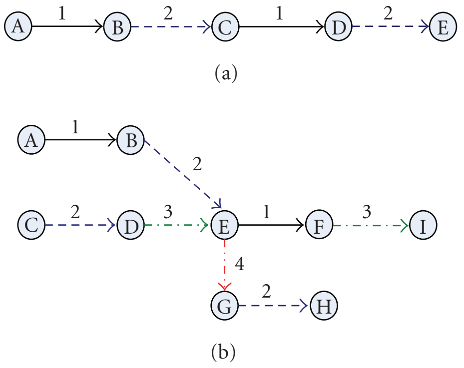


FIGURE 1: Channel allocation (indicated by numerical numbers) in multihop networks, an example.

3.1. Power control framework

The objective of power control is to minimize the total energy consumption, or equivalently, manage interferences intelligently to maximize the energy efficiency, and at the same time, guarantee certain level of QoS if feasible. In this paper, it is assumed that distinct channels are preassigned to avoid the primary conflict (a node cannot transmit and receive simultaneously [14]). It should be noted that the power control problem is formulated on a perchannel basis. In other words, only cochannel interference (the interference caused by transmitter-receiver pairs that use the same channel) needs to be addressed in a multihop network. An example channel allocation is shown for the end-to-end paths in Figure 1. Because a node cannot transmit and receive at the same time, the transmissions of the consecutive links along a path have to use different channels. For instance, in Figure 1(a), two channels are allocated. Active links A to B and C to D share channel 1, active links B to C and D to E share channel 2. Moreover, at the node where multiple paths cross such as node E in Figure 1(b), more channels may be necessary.

Assume that there are N_c transmitter-receiver pairs (active links) in the network using the same channel c, the power control problem can be formulated as follows:

(P.1)

$$\min_{p_i} \sum_i p_i, \quad i = 1, 2, \dots, N_c, \tag{1}$$

subject to the constraints

$$\begin{gathered} \gamma_i \ge \gamma_i^{\text{tar}}, \quad i = 1, 2, \dots, N_c, \\ 0 \le p_i \le p_i^{\max}, \quad i = 1, 2, \dots, N_c, \end{gathered} \tag{2}$$

where γ_i is the actual received SIR at receiver i, γ_i^{tar} is the target SIR of the ith active link, p_i is the transmission power of transmitter i, and $p_i^{\max}$ is the maximum power allowed for transmitter i.

The received SIR at receiver i is given by

$$\gamma_i = \frac{L h_{ii} p_i}{\sum_{j \ne i} h_{ij} p_j + \sigma^2}, \tag{3}$$

where h_{ii} is the link gain from transmitter i to its designated receiver. h_{ij} is the link gain from transmitter j to receiver i. p_i and p_j are the transmission power of transmitters i and j, respectively. σ^2 is the background noise. L is the spreading gain for spread spectrum systems, for example, a typical value of spreading gain $L = 64$ or 128 is used in CDMA systems. The general interference model adopted here assumes that each transmitting node in the network causes interference at any receiving nodes using the same channel, even if they are far apart [15]. This model is considered more realistic than the one which assumes that transmitting nodes only cause interference to their neighbors. This is because the aggregate interference from a large number of nodes may not be negligible even if interference from each of them is small.

Given the traffic flow with desired data rate R^{tar}, the corresponding target SIR can be expressed as

$$\gamma_i^{\text{tar}} = 2^{R_i^{\text{tar}}/W_i} - 1, \quad i = 1, 2, \ldots, N_c, \tag{4}$$

where W_i is the bandwidth occupied by the transmission from the ith transmitter to its designated receiver. $R_i^{\text{tar}} = n_i R^{\text{tar}}$, where n_i is the number of incoming and outgoing active links at the ith transmitter. Note that this formula (derived from the Shannon capacity formula) uses the achievable rate (upper bound) of the AWGN channel. However, it is justified by the fact that with the current modulation and coding technology it can be closely approximated in most practical scenarios [16].

3.2. Centralized solution

The following theorem gives the feasibility condition of the formulated power control problem (P.1).

Theorem 1. *A target SIR vector* $\boldsymbol{\gamma}^{\text{tar}}$ *is achievable for all simultaneous transmitting-receiving pairs within the same channel as long as the feasibility condition is met, that is, the matrix* $[I - \Gamma^{\text{tar}} Z]$ *is nonsingular (thus invertible) and the inverse is elementwise positive, where matrix* Γ^{tar} *is a diagonal matrix:*

$$\Gamma_{ij}^{\text{tar}} = \begin{cases} \gamma_i^{\text{tar}}, & i = j, \\ 0, & \textit{otherwise}, \end{cases} \tag{5}$$

and matrix Z is the following nonnegative matrix:

$$Z_{ij} = \begin{cases} \dfrac{h_{ij}}{L h_{ii}}, & i \neq j, \\ 0, & i = j. \end{cases} \tag{6}$$

The proof is given in the appendix. In the case of a CDMA network as considered in this work, since the processing gain L is a large positive number, the power control problem is usually feasible because the matrix $[I - \Gamma^{\text{tar}} Z]$ is a diagonally dominant matrix (see [17, Definition 6.2, page 151]). The spectral radius of $\Gamma^{\text{tar}} Z$ is less than 1 (see [17, page 151]) in this case. This is equivalent to the feasibility condition given in Theorem 1 [18].

Equation (A.6) in the appendix provides a centralized solution to the power control problem (P.1). Given the desired throughput, maximum allowable power, and bandwidth of each active link i (R^{tar}, $p_i^{\max}$, and W_i), it is straightforward to calculate the optimal power vector using

$$p^* = [I - \Gamma^{\text{tar}} Z]^{-1} u \tag{7}$$

provided that the link gain matrix is available.

An $N \times N$ link gain matrix H may be formed, where h_{ij} is the link gain from the jth transmitter to the ith receiver. Note that H is always a square matrix, where the column is indexed by transmitter and the row is indexed by the corresponding receiver.

3.3. Distributed schemes

The centralized solution (7) needs a central controller and *global* information of all the link gains. However, it is very difficult to obtain the knowledge of all the link gains in an infrastructureless wireless ad hoc network and it is usually impractical to implement a centralized solution. Also, even if centralized scheme were to be implemented, the amount of signaling overhead would increase significantly. Therefore, a distributed implementation is suggested for realistic scenarios.

Distributed power control schemes may be derived by applying iterative algorithms to solve (7). For example, using the first-order Jacobian iterations [17], the following distributed power control scheme (also known as DCPC [19, 20] for cellular wireless systems) is obtained:

$$p_i(k+1) = \min\left\{ \frac{\gamma_i^{\text{tar}}}{\gamma_i(k)} p_i(k), p_i^{\max} \right\}, \quad i = 1, 2, \ldots, N_c. \tag{8}$$

Note that each node only needs to know its own received SIR at its designated receiver to update its transmission power. This is available by feedback from the receiving node through a control channel. As a result, the algorithm is fully distributed. Convergence properties of this algorithm were studied by Yates [19]. An interference function $I(p)$ is standard if it satisfies three conditions: positivity, monotonicity, and scalability. It is proven by Yates [19] that the standard iterative algorithm $p(k+1) = I(p(k))$ will converge to a unique equilibrium that corresponds to the minimum use of power. The distributed power control scheme (8) is a special case of the standard iterative algorithm.

Since the Jacobi iteration is a fixed-point iterative method, it usually has slow convergence speed to the sought solution. However, we select DCPC (8) as the power control algorithm in our proposed power-aware maximally disjoint routing due to its simplicity. Other advanced algorithms with faster convergence speed can be found in [21–23].

The complete procedures of obtaining a power-controlled connectivity graph using a distributed algorithm are highlighted in Figure 2. The procedures will be executed for

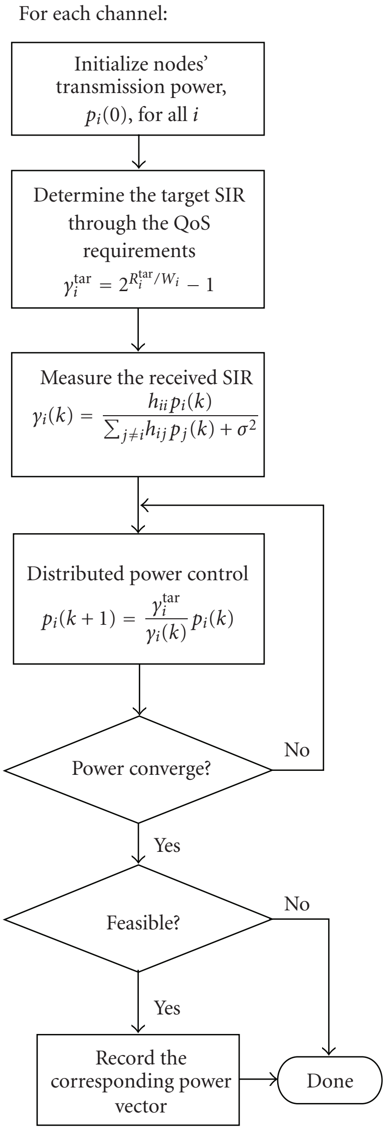


FIGURE 2: Distributed algorithm for power-controlled connectivity graph.

all the channels. The success of concurrent transmissions within each channel is guaranteed by power control.

4. PROPOSED POWER-AWARE MAXIMALLY DISJOINT ROUTING

In a mobile wireless ad hoc network, node failures (due to energy loss) and link failures (due to node mobility, channel fluctuation) are common and present a great challenge to reliable data delivery. The proposed power-aware maximally disjoint routing is based on providing fault tolerant disjoint multipath technique to mitigate the effect of constantly changing network topologies and wireless channels.

There are two types of disjoint paths, namely, node-disjoint paths and link-disjoint paths. Node-disjoint paths are also link-disjoint, but not vice versa. An example is illustrated in Figure 3. Paths R1 and R3 are node-disjoint paths (hence link-disjoint as well) since they do not share any node (except the source node A and the destination node L). On the other hand, paths R2 and R3 are link-disjoint paths because they have no common links. However, they are not node-disjoint. In this paper, only node-disjoint paths are considered since they are more fault tolerant than link-disjoint paths.

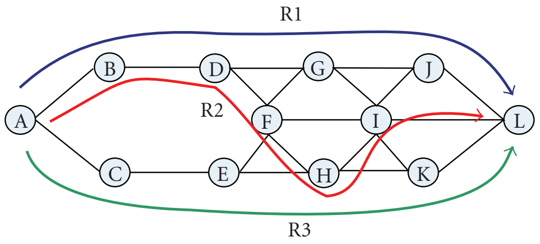


FIGURE 3: Node-disjoint versus link-disjoint paths.

There are two ways of using the multiple paths to send data. The first approach is to send data along multiple paths *simultaneously* to achieve diversity. Examples of simultaneous transmission to achieve diversity are to send either the same data packets for redundancy [8], or different subpackets using diversity coding [24, 25]. The second approach is to send data through only one path, while using the other paths as backup. Although the second approach is widely used in wired networks such as in optical networks, it has not been considered for mobile wireless ad hoc network in the literature according to our best knowledge. The argument has been the duplicity of bandwidth and therefore for bandwidth-starved wireless networks, this is a critical problem.

In our solution, we are using the second method and we are not reserving the bandwidth on the backup path. The sender keeps track of the bandwidth availability and maintains the backup path. When the primary path has failed and is not available, the backup path bandwidth is used. Therefore, for each user application, the required bandwidth is always the same and not duplicated. This solution has the following advantages.

(1) There is no complicated diversity coding scheme required. Thus, there is no excessive delay induced by waiting subpackets from the slow path to arrive before a packet can be successfully decoded.

(2) Different traffic flows, whether they have the same source and destination or not, may share the links in their respective backup paths. This results in a much better bandwidth utilization comparing to the first approach.

(3) The packet reordering at the destination node during the transient phase (due to traffic shift) is much less frequent than the subpacket reordering needed constantly in the first approach.

The disadvantage of the second approach is that traffic may shift back and forth if node mobility is changing much faster (orders of magnitude) than the duration of the traffic sessions. We propose a hysteresis rule for traffic shifting to mitigate this effect, as explained in detail in Section 5. Moreover, we should emphasize that the time constant of the mobility is on the same order or less of the duration of the traffic sessions considered in this paper.

4.1. Routing algorithm

Although the power expenditure along a route is the main concern here, other network resources such as the number of transceivers and the number of channels are also important for the success of routing, especially in the case of connection-oriented traffic [14]. In practice, routing can be done by excluding those nodes with insufficient transceivers from the topology of the network. In addition, there exist many algorithms that find efficient channel allocations, for example, see [26] and the references therein. Hence, it is assumed in this paper that enough transceivers are available and proper channel allocations have been done before routing.

The routing problem is defined as follows.

(P.2) *Given the network resources at each node (such as the number of transceivers and channel allocations), find the most energy-efficient path and a maximally disjoint backup path for a given traffic flow with required throughput in the power-controlled connectivity graph.*

For our approach, we consider split multipath routing (SMR), introduced by Lee and Gerla [10], as the background routing research. SMR is an on-demand routing protocol that constructs "maximally disjoint paths." SMR is based on dynamic source routing (DSR) [27] but uses a different packet-forwarding mechanism. While DSR discards duplicate routing request (RREQ), SMR allows intermediate nodes to forward certain duplicate RREQ in order to find more disjoint paths. In SMR, intermediate nodes forward the duplicate RREQ that traversed through a different incoming link than the link from which the first RREQ is received, and whose hop count is not larger than that of the first received RREQ. In SMR, minimum power resolution is not a criterion and no desired throughput is considered. Our approach is to enhance SMR with both minimum power and balanced energy to address minimum power resolution and maximize network lifetime.

(i) Minimum power split multipath routing (MPSMR) with maximally disjoint paths

MPSMR is based on SMR. However, in MPSMR, the transmission power is used as the link metric instead of hop count. Each RREQ has a field that records the total transmission power along a path and keeps updating the field while traversing through the network. The intermediate nodes forward the duplicate RREQ whose total power is not larger than that of the first received RREQ. The destination will choose the path with the least total transmission power and a maximally disjoint backup path.

(ii) Balanced energy split multipath routing (BESMR) with maximally disjoint paths

Instead of the transmission power, the metric p_i/E_i is proposed to balance the power efficiency and fairness among nodes. p_i and E_i are the transmission power and the remaining energy of node i, respectively. BESMR selects route that minimizes $\sum(p_i/E_i)$. It considers the tradeoff between transmission power and the remaining energy of a node, thus maximizing the network's lifetime. Note that BESMR also reduces network congestions because traffic will be distributed more evenly across the network, rather than aggregated among a small set of nodes where transmission power is low.

Remark 1. In [8], a simplified interference model is used. The simplified interference model assumes that there is no interference from other transmissions, and the SIR of each link depends solely on its own received power and background noise, that is,

$$\gamma_i = \frac{h_{ii} p_i}{\sigma^2}, \tag{9}$$

where h_{ii} is the link gain from transmitter i to its designated receiver i. σ^2 is the background (receiver) noise. When the simplified interference model is applied, it is straightforward to calculate the transmission power of each link i along a path:

$$p_i = \frac{\gamma_i \sigma^2}{h_{ii}}. \tag{10}$$

However, since a realistic interference model (3) is used in this paper, an iterative algorithm is necessary to determine the transmission power and the maximally disjoint paths jointly. The procedures are listed below.

(1) The transmission power of all links is initialized to the minimum power specified by the standard. Initial two maximally disjoint paths are calculated using $\sum p_i$ (for MPSMR) or $\sum(p_i/E_i)$ (for BESMR) as the routing metric. Then the transmission power along these two disjoint paths is updated using distributed power control (8) discussed in the Section 3.

(2) Two new maximally disjoint paths are calculated using $\sum p_i$ (for MPSMR) or $\sum(p_i/E_i)$ (for BESMR) as the routing metric.

(3) If the routing metric of the two new paths is less than that of the previous two paths, then update the transmission power along these two new paths using distributed power control. Go to step (2). Otherwise, select the two disjoint paths found in the previous iteration, and done.

The above iterative algorithm is illustrated in Figure 4.

Note that the proposed iterative algorithm is also valuable for call admission control. If the power control problem becomes infeasible due to a new traffic session, it will be rejected.

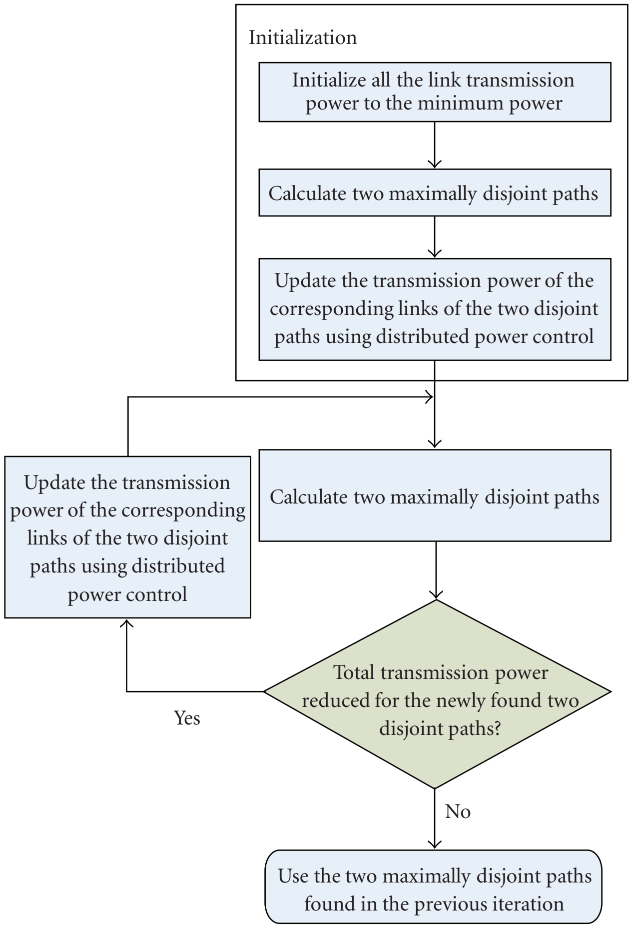


Figure 4: An iterative algorithm for joint power control and maximally disjoint routing.

5. DYNAMIC TRAFFIC SWITCHING

The joint power control and routing scheme will be applied before each traffic session starts. In order to guarantee the required data throughput with high probability during the entire session of the traffic flow, an online dynamic traffic restoration scheme is indispensable to deal with node mobility or node failure. In this paper, only "soft QoS" [3] is supported. In other words, there may be short transient period where QoS requirements are not guaranteed due to path break or reduced capacity. However, the QoS requirements will be ensured when the path is not broken or after the session is switched to a new path. Note that many multimedia applications accept soft QoS and use rate adaptive schemes to mitigate disruptions, for example, see [5].

There are several phases in the proposed dynamic traffic switching (restoration) scheme.

(1) Initialization phase: given the topology of a wireless ad hoc network, MPSMR or BESMR is used to find two maximally disjoint paths from the source to the destination such that the corresponding power control problem is feasible. If such paths cannot be found, the traffic session is rejected. Otherwise, go to the next step.

(2) Monitoring phase: the source node saves the two paths in its routing table and starts to send packets through the primary path. At the same time, the source also sends small amount of probe packets to monitor both paths.

(3) Path-switching (transient) phase: the source node monitors the throughput, delay, and loss of both two paths. If the throughput is below a threshold R_{th}^1, the node shifts the data traffic from the current path to the backup path. At the same time, it starts a new RREQ using MPSMR or BESMR, and stores the newly found paths in the routing table as the new backup paths.

(4) Convergence phase: if the throughput of the original path improves and increases beyond a threshold R_{th}^2, the node will shift the data traffic from the current path back to the original path.

One example of the implementation of the probe mechanism is given in [28]. The choices of the thresholds R_{th}^1 and R_{th}^2 depend on the traffic type (such as the compression ratio in MPEG-4) and the characteristics of the wireless ad hoc network such as node density and node mobility. Delay and loss of the path may be used to determine the traffic switching as well. The number of backup paths is another design parameter. Note that a small amount of drop in throughput may be compensated by adaptive modulation and coding schemes.

In order to implement the proposed scheme, a software agent for traffic monitoring and switching is installed at each node in the network. The block diagram of the agent is shown in Figure 5.

Usually we expect that traffic switches randomly due to the random nature of the mobility pattern of mobile users, the resulting topology changes and interferences. However, it may happen that two or more traffic flows switch to paths that share the same links simultaneously. These links have a potential to be congested and the traffic flows switch simultaneously from these links. This causes instability in traffic switching. It is resolved by enabling the source to wait a short random time before switching.

6. PERFORMANCE EVALUATION

The performance of the proposed joint power control and maximally disjoint routing is evaluated through discrete-event simulations using OPNET. The results are compared with SMR. The dynamic traffic switching scheme is also tested.

6.1. Simulation setup

In this simulation study, it is assumed that there is a fixed number ($M = 50$) of nodes located in a square area (300 m × 300 m). The locations of the nodes are uniformly distributed within the area. The other parameters include the following.

(1) The required throughput is $R_i^{\text{tar}} = 250$ kbps for all the traffic sessions.

(2) The bandwidth shared by all links is 1.25 MHz.

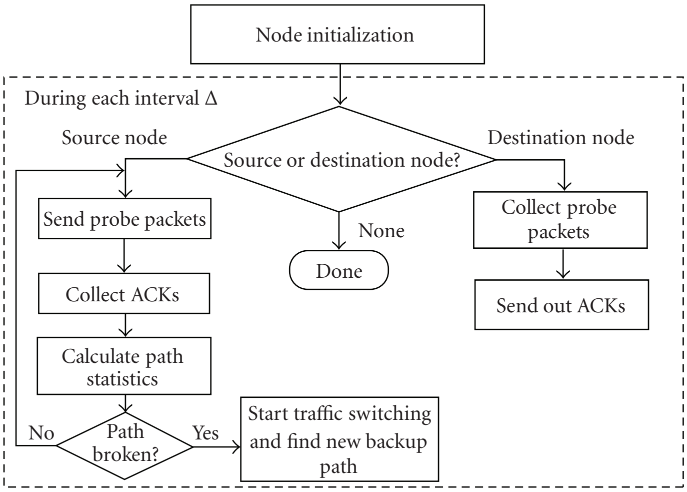


Figure 5: Software agent for traffic monitoring and switching.

(3) The link gains are assumed to be only function of distance, that is, $h_{ij} = 1/d_{ij}^{\alpha}$, where $\alpha = 4$. No fading is considered here.

(4) The maximum allowable transmission power $p^{\max}$ is 200 mW.

(5) The background noise is $\sigma^2 = 10^{-7}$.

In addition, all the nodes are assumed stationary or have negligible mobility during the entire routing process such that routing and QoS provisioning will not become meaningless. However, nodes may move dramatically during traffic sessions (data forwarding).

6.2. *Maximally disjoint routing with different interference model*

In this part of the simulations, source and destination are randomly chosen and the MPSMR algorithm is used to find two maximally disjoint paths with low-energy expenditure. Three cases are examined with different interference model: (1) the simplified interference model (the best case); (2) the general interference model including *all* links (the worst case); (3) the general interference model including only the links within the two maximally disjoint paths. Note that the worst case scenario corresponds to the QoS provisioning considered in [9].

In order to compare joint power control and routing schemes with different interference models, the following performance criteria are selected: (1) average success probability (p_{succ}); (2) energy per bit (E_b). The first criterion (p_{succ}) focuses on the average traffic carrying capability of the network, while the second criterion (E_b) quantifies the energy efficiency of the proposed schemes.

Table 1: Comparison of routing schemes with different interference models.

Case	p_{succ}	E_b (in $\times 10^{-6}$ Joule/bit)	Computational complexity
1	0.99	0.12	Low
2	0.13	0.18	High
3	0.75	0.14	High

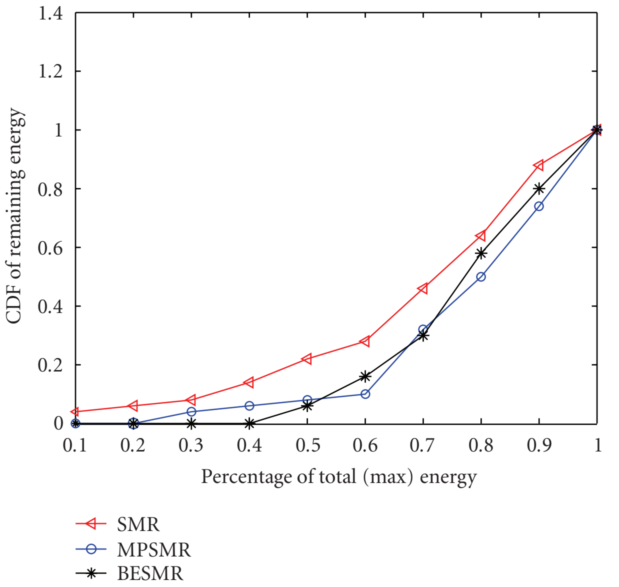


Figure 6: The cumulative distribution function (CDF) of the remaining energy at each node.

The simulation results are averaged over 100 routing attempts and are summarized in Table 1. It is clear that routing with the simplified interference model gives the best success probability and energy efficiency as expected. However, this model is too optimistic because it ignores all the interferences. If all links (whether have data to transmit or not) are included in the interference model, we get the worst performance due to unnecessary conservativeness. However, it may be useful when the network is heavily loaded. The performance of the proposed method is somewhere in between and reflects the realistic situations.

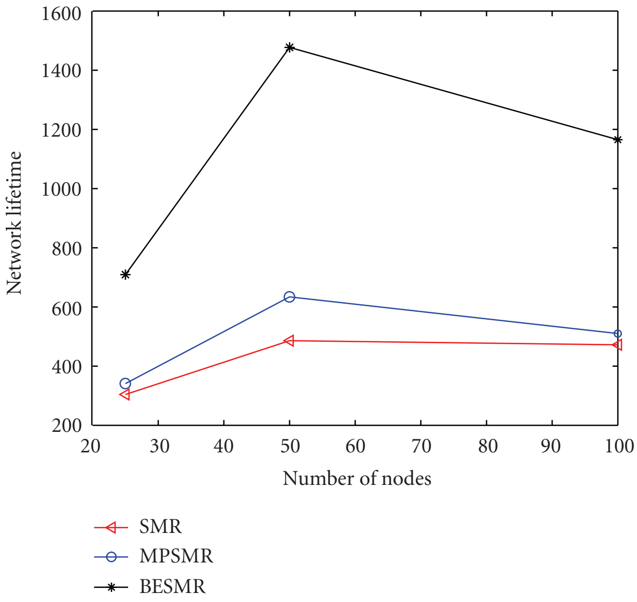


Figure 7: Network lifetime.

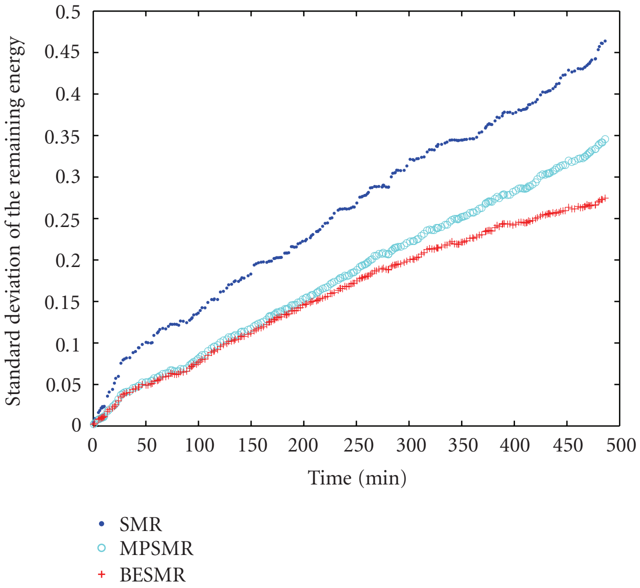


Figure 8: Standard deviation of the remaining energy at each node (50 nodes).

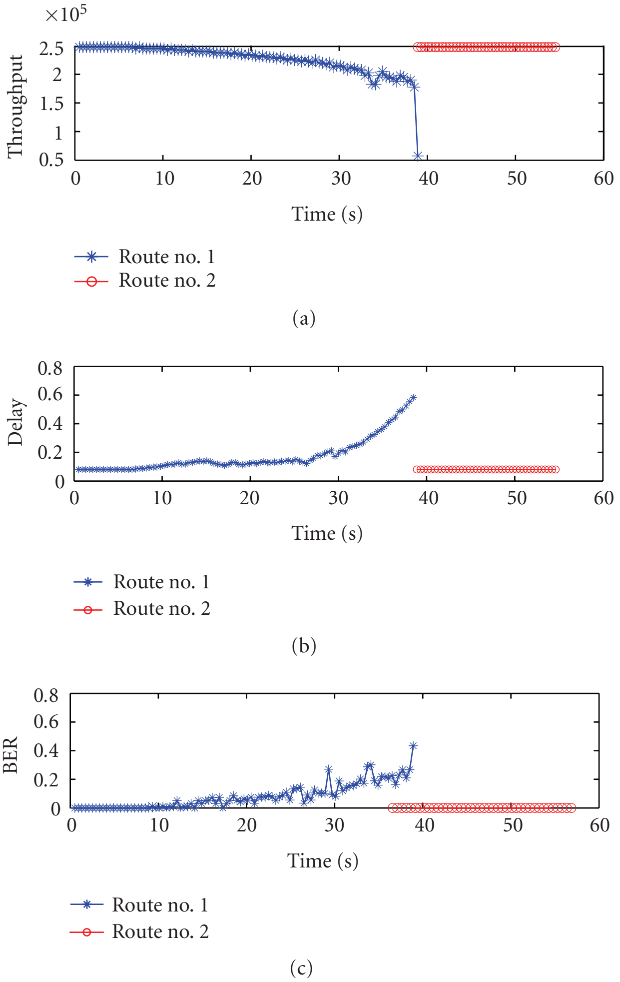


Figure 9: Performance index (throughput, delay, and BER) during traffic switching due to node mobility.

6.3. *Comparison of SMR, MPSMR, and BESMR*

The performances of SMR, MPSMR, and BESMR are compared in terms of energy efficiency and network lifetime. The network lifetime is defined as the time of the first node failure (because of running out of energy). It is assumed that all nodes have the same initial energy at the start of the simulation. The source and destination of each traffic session are randomly chosen. The duration of the traffic sessions is assumed to be exponentially distributed with mean equal to 1 minute. Energy efficiency is measured by the cumulative distribution function (CDF) of the remaining energy at each node after the shortest lifetime of the three routing algorithms.

Figure 6 depicts the CDF of the remaining energy at each node after the lifetime of SMR (which is the shortest among the three). It indicated that both MPSMR and BESMR have better energy efficiency than SMR (by about 15%). All nodes have more than 40% energy left using BESMR which indicates that BESMR has balanced energy usage among nodes. There are about 8% of the nodes which are heavily used (have less than 40% energy left) when MPSMR is applied.

The network lifetime using SMR, MPSMR, and BESMR is shown in Figure 7 for networks with 25, 50, and 100 nodes, respectively. It is clear that BESMR has the longest network lifetime because of its fairness to all nodes. A closer look at the standard deviation of the remaining energy at each node along time (Figure 8) explains that BESMR tends to balance the energy consumption among all nodes, thus, has the smallest standard deviation, and hence the longest network lifetime.

6.4. Dynamic traffic switching

The proposed dynamic traffic switching scheme is tested by letting a randomly selected node (other than the source and destination) on the primary path leave the area (thus break the primary path) during the process of data transmission. The threshold R_{th}^1 is set to 80%.

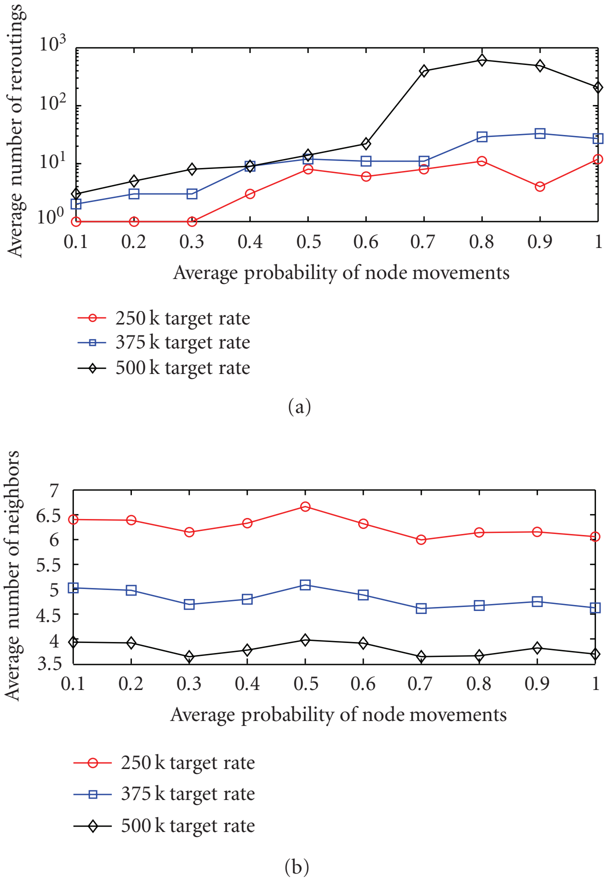
Figure 9 shows the performance of the proposed traffic switching scheme when the primary path (route no.1) is broken due to node mobility. When the throughput of the primary path (route no.1) drops below 80% of the desired throughput, the traffic will be switched to the backup path (route no.2). The corresponding end-to-end delay and bit-error rate (BER) are also shown. We assume that there is only one node moving in this simulation.

6.5. The effect of node mobility

In this part of the simulation, it is assumed that all nodes in the network are mobile and they move according to the following "random waypoint" mobility model [27]: at the beginning of each time interval, each node decides to move with probability $0 \leq q \leq 1$. If a node decides to move, it will choose a random destination and a speed vector will be sampled from a uniformly distributed random variable $v \sim [v^{\min}, v^{\max}]$, where v is the value of the speed. $v^{\min} = 0.3$ m/s and $v^{\max} = 0.7$ m/s are the lower and upper bounds of the speed, respectively.

The average number of rerouting and the average number of "effective neighbors" versus node mobility (q) are shown in Figure 10. The results are averaged over 100 traffic sessions. The source and destination of each traffic session are randomly chosen. The duration of each traffic session is assumed to be exponentially distributed with mean equal to 1 minute. Here, node B is called an "effective neighbor" of node A if they are neighbors and the supported data rate between A and B is above the target data rate.

It can be observed that the number of rerouting increases with the required data rate, as expected. The number of rerouting increases with q from 0 to 0.3, however, it almost remains constant after that for low-to-moderate required data rate. This can be explained by the average number of "effective neighbors" shown in the same figure. The average number of "effective neighbors" drops with q, however, there are still enough "effective neighbors" for low-to-moderate required data rate. For example, there are 6 "effective neighbors" on average when $R^{\text{tar}} = 250$ kbps even when all nodes are constantly moving ($q = 1$). There are less "effective neighbors" on average for high required data rate ($R^{\text{tar}} = 500$ kbps). The average number of neighbors drops to only 3 when all nodes are constantly moving ($q = 1$). The above simulation results are critical for network operators to set call admission control policies. Based on the estimated node mobility, traffic session duration, and QoS requirements, the average number of rerouting can be estimated. Thus, the cost of supporting the traffic session with QoS can be calculated and call admission control decision can be made accordingly.



(a)

(b)

Figure 10: Average number of rerouting and average number of neighbors versus node mobility.

6.6. Overhead and scalability analysis

In this part of the simulation, the proposed joint power control and routing plus traffic switching scheme is tested in a realistic environment. A similar setup as in Section 6.1 is used with the following changes.

(1) There are 80 nodes in a constrained area of 450 m × 450 m.

(2) The simulation time is 10 minutes.

(3) It is assumed that the link gains have the following form:

$$h_{ij}(k) = d_{ij}^{-4}(k) A_{ij}(k) B_{ij}(k), \tag{11}$$

where $d_{ij}(k)$ is the distance from the jth transmitter to the ith receiver at time instant k, A_{ij} is a lognormal distributed stochastic process (shadowing), and B_{ij} is a fast fading factor (Rayleigh distributed).

(4) It is assumed that the standard deviation of A_{ij} is 8 dB [29].

Table 2: Performance results of routing and data delivery.

Node velocity	Packet delivery ratio		Total number of traffic switching		Total cost per routing (in number of routing packets)	
(m/s)	1 pair	10 pairs	1 pair	10 pairs	1 pair	10 pairs
0	0.99	0.99	0	0	47 558	55454
1	0.98	0.95	1	20	47 226	71 450
10	0.67	0.6	11	90	56 135	90 398
20	0.46	0.39	15	110	79 989	83 516
30	0.44	0.39	11	123	82 180	68 751

(5) It is assumed that the Doppler frequency is from 8 Hz (for pedestrian mobile users) to 80 Hz (for mobile users at vehicle speed) [29].

(6) All nodes in the network are constantly moving according to the "random waypoint" mobility model [27], with pause time set at 10 seconds and five different velocities from 0 m/s for stationary nodes to 30 m/s for mobile users at vehicle speed.

(7) Two cases with a single source/destination pair and 10 pairs are tested, respectively. All the sources are assumed to generate data packets for transmission continuously at the target rate throughout the simulation. The mean packet size is 1024 bits.

The results are summarized in Tables 2 and 3. MPSMR is chosen as the routing scheme. It is observed that there is almost no packet loss in the case of a stationary network. Routing is only needed once for each source/destination pair, and traffic switching is not required, as expected. It is also observed that the packet delivery ratio drops dramatically when all the nodes become mobile and reach vehicle speed, because the number of broken paths (thus traffic switching) increases significantly. However, it is interesting to see that 10 source/destination pairs do not overload the network yet, and the performance results (in terms of packet delivery ratio, number of traffic switching, and cost of routing) are comparable to the case of a single source/destination pair. The main reason is that data are only transmitted through one path in the proposed scheme rather than through multiple paths simultaneously, thus it avoids overloading the network. The routing overhead may be calculated as follows:

$$\begin{aligned}\eta = {} & (\text{no. of routing packets} \times \text{average routing packet size} \\ & \qquad \times \text{ no. of routing per pair})/ \\ & (\text{data rate} \times 600\,\text{s} \times \text{average no. of hops per path} \\ & \qquad \times \text{packet delivery ratio}).\end{aligned} \tag{12}$$

Note that the routing overhead is about 20% in the worst case (10 source/destination pairs, 20 m/s), where the average routing packet size is 64 bits and the average number of hops per path is 5.

The distributed power control scheme requires that the receivers provide the received SIR value (or equivalently, the link gain) to the corresponding transmitters. The power control overhead is evaluated by the number of the control packets needed for these information exchange. It is shown in Table 3 that the proposed joint power control and routing scheme converges in about 5 to 6 iterations in all cases. In addition, the power control overhead does not increase too much with respect to node mobility and number of source/destination pairs. In other words, the proposed scheme exhibits reasonable scalability in highly mobile and high traffic load environment. Note that supporting energy efficient QoS routing in a larger network that has thousands or more nodes needs very careful architectural design, such as a cluster-based architecture and management, which is out of the scope of this paper.

Table 3: Convergence and overhead of the proposed scheme.

Node velocity	Number of iterations per routing		Power control overhead per iteration (in number of control packets)	
(m/s)	1 pair	10 pairs	1 pair	10 pairs
0	6	6.9	405	405
1	5.33	5.36	642	644
10	5.19	5.99	586	598
20	5.38	5.76	569	590
30	5.88	5.64	533	561

7. CONCLUSIONS

In this paper, a joint power control and maximally disjoint routing algorithm is proposed and analyzed for routing traffic between one source and destination pair with high energy efficiency. In addition, a dynamic traffic switching scheme is proposed to mitigate the effect of node mobility or node failure. Together they provide a means for reliable end-to-end data delivery with guaranteed throughput. Moreover, the tradeoff between energy efficiency and network lifetime is also taken into consideration by using different routing metrics. The effectiveness of the proposed scheme is demonstrated through discrete event simulations.

The proposed joint power control and maximally disjoint routing is based on SMR, a multipath source routing algorithm. Extensions of the proposed scheme to other popular ad hoc routing algorithms such as ad hoc on-demand multipath distance vector (AOMDV) [13] are underway. The extension of the current scheme to wireless networks employing dynamic scheduling such as the algorithms in [30] would be another interesting future research topic.

APPENDIX

PROOF OF THEOREM 1

Proof. A target SIR vector $\boldsymbol{\gamma}^{\mathbf{tar}}$ is achievable for all simultaneous transmitting-receiving pairs within the same channel if the following conditions are met [18, 21]:

$$\gamma_i \geq \gamma_i^{\text{tar}}, \qquad p \geq 0, \tag{A.1}$$

where p is the vector of transmitting powers. Replacing γ_i with (3) and rewriting the above conditions in matrix form give

$$[I - \Gamma^{\text{tar}} Z] p \geq u, \quad p \geq 0, \tag{A.2}$$

where matrix Γ^{tar} is a diagonal matrix:

$$\Gamma_{ij}^{\text{tar}} = \begin{cases} \gamma_i^{\text{tar}}, & i = j, \\ 0, & \text{otherwise} \end{cases} \tag{A.3}$$

and matrix Z is the following nonnegative matrix:

$$Z_{ij} = \begin{cases} \dfrac{h_{ij}}{Lh_{ii}}, & i \neq j, \\ 0, & i = j, \end{cases} \tag{A.4}$$

u is the vector with elements

$$u_i = \frac{\gamma_i^{\text{tar}} \sigma^2}{Lh_{ii}}, \quad i = 1, 2, \ldots, N. \tag{A.5}$$

It is shown in [18] that if the system is feasible, the matrix $[I - \Gamma^{\text{tar}} Z]$ must be invertible and the inverse should be elementwise positive, thus prove the theorem.

It is also shown in [18, Proposition 2.1] that if the system is feasible, there exists a unique (Pareto optimal) solution which minimizes the transmitted power. This solution is obtained by solving a system of linear algebraic equations

$$[I - \Gamma^{\text{tar}} Z] p^* = u. \tag{A.6}$$

□

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