Reliable and Energy-Efficient Routing for Static Wireless Ad Hoc Networks with Unreliable Links

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Abstract—Energy efficient routing and power control techniques in wireless ad hoc networks have drawn considerable research interests recently. In this paper, we address the problem of energy efficient reliable routing for wireless ad hoc networks in the presence of unreliable communication links or devices or lossy wireless link layers by integrating the power control techniques into the energy efficient routing. We consider both the case when the link layer implements a perfect reliability and the case when the reliability is implemented through the transport layer, e.g., TCP. We study the energy efficient unicast and multicast when the links are unreliable. Subsequently, we study how to perform power control (thus, controlling the reliability of each communication link) such that the unicast routings use the least power when the communication links are unreliable, while the power used by multicast is close to optimum. Extensive simulations have been conducted to study the power consumption, the end-to-end delay, and the network throughput of our proposed protocols compared with existing protocols.

Index Terms—Wireless ad hoc networks, power assignment, reliable communication, energy efficiency.

1 INTRODUCTION

Wireless ad hoc networks draw lots of attentions in recent years due to its potential applications in various areas. Many routing protocols have been proposed for wireless ad hoc networks. In many scenarios, design of wireless protocols is guided by two essential requirements: energy efficiency and resilience to packet losses. Efficiently handling losses in wireless environments, therefore, has significant importance. Even under benign conditions, various factors, like fading, interference, multipath effects, and collisions, lead to heavy loss rates on wireless links. Due to the end-to-end reliability requirement of many applications, it is necessary to study how such reliability can be guaranteed in an energy efficient way in wireless environments. In this paper, we study how to achieve reliable and energy efficient routing in multihop wireless networks, where each wireless link and device could be unreliable. We propose several novel methods (both centralized and distributed) that appropriately handle packet losses by systematically integrating the energy efficient routing, reliability, and power control techniques.

A number of energy efficient routing protocols [1], [2], [3], [4], [5] have been proposed using a variety techniques (dynamic transmission power adjustment, adaptive sleeping, topology control, multipath routing, directional antennas, etc.). The conventional power aware routing protocols did not take into account the reliability of the wireless links. It is often assumed that the wireless links of a wireless network are reliable by these traditional protocols with certain theoretically proven performance guarantees [5], [6]. This is clearly too optimistic since in practice, the wireless communications are unreliable and often unpredictable. A number of protocols have been proposed recently to remedy the unreliability of the wireless channels such as using multipath routing [7], [8], building reliable backbone [6], [9], and using energy-efficient reliable routing structure [10], [11], [12].

Observe that the wireless link reliability depends on many factors such as weather, the transmission power, the receiver’s sensitivity, and so on. Obviously, one can increase the transmission power to improve the link reliability and consequently reduce the retransmission times potentially. However, this is not free: we do consume more power for single transmission. In this paper, we seek the balance of the smaller transmission power and lower link error rate.

The main contributions of this paper are follows: We integrate the energy efficient routing and power assignment into one scheme by considering the link error rate as a certain function of the transmission power. Notice that when the power used to support the communication of every link is given, the expected link error rate could be derived. Thus, the path with the minimum expected power consumption connecting any two nodes can then be found [11]. When the transmission power changes, the shortest path found will likely change also. Given a fixed source node (or a destination node), we propose algorithms to find the optimal power...
assignment for every link such that the expected power consumption of the unicast from the source node to every other node in the network is the minimum among all possible power assignments. The expected energy consumption depends on the power assignment to all links since the expected link error rate is a function of the transmission power; on the other hand, the optimal power assignment needs the algorithm to find the path with the minimum expected power consumption. We consider two different scenarios: either the link layer reliability or the transport layer reliability is implemented. Notice that, in practice, a certain link layer reliability is already implemented in the MAC layer. Our second contribution is the study of integrated power assignment and energy efficient routing using multipath routing techniques. Our third contribution is a multicast method that integrates the optimal power assignment and energy efficient multicast tree construction. In our multicast method, we assume an overlay based multicast. We theoretically prove that our multicast routing is almost optimal: the expected total power consumption of the constructed multicast tree is within a small constant factor of the optimum. We conduct extensive simulations to study the performance of our protocols. Our simulations show that our protocols significantly reduce the expected energy consumption of routing. The main differences of our result with the result recently presented in [10] and [11] are as follows: 1) we integrate the power assignment and energy efficient routing, while [10] and [11] only focuses on energy efficient routing; 2) we also consider the power efficient multicast, which is not considered in [10] and [11]; and 3) we perform a more realistic simulation to study the performance of our protocols, and the simulations show a significant improvement over previous method in terms both expected energy consumption and network throughput.

The rest of the paper is organized as follows: Section 2 describes our network model, the problems to be studied, and the related works. In Section 3, we present our centralized/distributed methods that integrate the power assignment, energy efficient routing, and reliability. We study the minimum energy reliable routing using multipaths in Section 4 and the energy efficient multicast in Section 5. We report simulation results in Section 6 and conclude the paper in Section 7.

2 Preliminaries and Network Model

2.1 Network Model

We assume that a set \( V \) of \( n = |V| \) wireless devices (called nodes hereafter) is distributed in a region. Each node is assigned a unique ID \( i \in [1, n] \). Additionally, each node \( i \) has a maximum transmission power \( \mathbb{P}(i) \). The multihop wireless network is then modeled by a directed communication graph \( G = (V, E) \), where \( E \) is the set of \( m = |E| \) directed links, and a directed link \( (u, v) \) belongs to \( E \) if and only if node \( v \) can receive the signal sent from \( u \) directly when \( u \) transmits at a power \( \mathbb{P}(u) \).

For a specific task, we need to assign the power to each wireless node (or link) such that the induced networks can meet the requirement of this task. For an example of unicast from source node \( s \) to a target node \( t \), we assign a power to all wireless links. Let \( p(u, v) \) denote the power assigned to node \( u \) to transmit signal from \( u \) to \( v \). We always assume that this power can maintain a reasonably good communication link quality\(^2\) from node \( u \) to node \( v \). This power \( p(u, v) \) could be fixed throughout the network operations if no power control techniques are employed, or it could be changed dynamically when it is needed by the power control techniques or to ensure energy efficient routing. It is well-known that the wireless propagation suffers severe attenuation. Let \( \|uv\| \) denote the euclidean distance between two wireless nodes \( u \) and \( v \). If node \( u \) transmits at a power \( P_t(u) \), the power of the signal received at a node \( v \) is assumed to be \( P_t(v) = \frac{P_t(u)}{g(u, v)} \), where \( g(u, v) \) is the wireless gain between node \( u \) and \( v \). It is commonly assumed in the literature that we can always correctly decode the signal when the received power \( P_t(v) \) satisfies that \( P_t(v) \geq \beta_0 \cdot N_0 \), where \( \beta_0 \) is the required minimum signal-to-interference-noise ratio (SINR), and \( N_0 \) is the strength of the ambient noise. Here, the constant \( \beta_0 \) is technology dependent. Thus, by assuming that the node \( u \) transmits at power \( P_t(u) \geq \beta_0 \cdot N_0 \cdot g(u, v) \), it is assumed in the literature that we can guarantee that node \( v \) will receive the signal correctly. In practice, this is not the case though. When a node \( u \) transmits at a power \( p \) to another node \( v \), the link \( (u, v) \) has a packet error probability \( \mathcal{E}_{u,v}(p) \) dependent on the transmission power \( p \). Notice that the packet error probability also depends on other factors, such as the environment, the digital modulation techniques, and so on. Since the power is the only factor we will control, we assume that this link error probability \( \mathcal{E}_{u,v}(p) \) (which is derived from the bit-error-rate BER) only depends on the transmission power \( p \) for a specific pair of nodes by assuming all other factors are fixed. For convenience, we use \( \mathcal{E}_{u,v}(p) \) to denote the link error probability \( \mathcal{E}_{u,v}(p(u, v)) \) of a link \((u, v)\) when the link power is assigned by a method \( p \).

We also assume that for each node \( u \), there is a node error probability \( \mathcal{E}_u \) such that when node \( u \) is asked to relay a certain message, it may make a mistake (such as dropping the packets) with probability \( \mathcal{E}_u \). This could happen due to many reasons such as the congestion, queue-buffer overflow, nodes’ movement, nodes’ sleep, or a sheer failure. Notice that the node error probability can be integrated into the link error probability as follows: For every link \((u, v)\), we define a new link error probability as

\[
\mathcal{E}_{u,v} = 1 - (1 - \mathcal{E}_{u,v}(p)) 
\]

In other words, when the receiving node \( v \) makes an error (thus, it cannot forward the data further), it is equivalent to say that node \( v \) did not get the data at all due to the error by link \((u, v)\). Consequently, for the remaining of the paper, we always assume that the node will not have error by integrating its error to the incoming links. Notice that the error of the transmitting node \( u \) is already integrated to the error by previous in-coming link of \( u \), since the error at a single node \( u \) should not be double counted.

1. Since the links are unreliable (could be broken with certain probability), the energy consumption of a unicast is a random variable.

2. In practice, it often means that the link error probability is not larger than a certain threshold.
2.2 Reliable Communication under Unreliable Links

Obviously, as long as there is some link in the multihop path that cannot guarantee reliable packet delivery, we will have to rely on TCP-like transport protocols to initiate end-to-end retransmissions starting from the source if end-to-end reliability is required. Assume that we want to implement a reliable communication from the source node s to a target node t. We further assume that a simple path \( v_{i_1}, v_{i_2}, \ldots, v_{i_k} \) is used for routing, where \( s = v_{i_1}, t = v_{i_k}, \) and direct links \( v_{i_j}, v_{i_{j+1}}, 1 \leq j \leq h - 1, \) belong to the network G. There are two possible approaches to implement a reliable communication in practice:

1. **Reliable link layer.** If the transmission from a node \( v_{i_j} \) to node \( v_{i_{j+1}} \) is not successful, node \( v_{i_j} \) will resend the data till node \( v_{i_{j+1}} \) successfully receives the data.

2. **Reliable transport layer.** If the transmission from node \( v_{i_j} \) to node \( v_{i_{j+1}} \) is not successful, node \( v_{i_j} \) will discard the data and, thus, the source node s will start the retransmission due to the time-out signal.

Notice that, in the second model, all transmissions started from the source node s (except the last successful one) are wasted.

2.3 The Problems: Minimum Energy and Reliable Routing

The minimum energy and reliable unicast routing problem (abbreviated as MEERR) is, given the power \( p(u, v) \) assigned to each link \((u, v)\) and the corresponding link error probability \( E_{u,v}(p) \), to find a route from the source node to the receiver such that the expected total energy used by all wireless nodes is minimized when either reliable link layer or reliable transport layer is implemented. This has been studied recently in [10] for reliable link layer and in [11] for reliable transport layer.

In this paper, we will study the following problems, which are different from MEERR [10], [11]:

1. **Power assignment for unicast.** Obviously, the final path found depends on the power \( p(u, v) \) used by link \((u, v)\). Then, the problem of power control for reliable energy efficient unicast is to find a power assignment \( p(u, v) \) for each link \((u, v)\) such that the minimum energy efficient reliable route from the source node to the receiver consumes the least expected energy among all possible power assignments. In this paper, we will first study the problem of finding a power assignment for every link and the corresponding path between the source and the target node with the minimum expected energy consumption, when either a reliable link layer is implemented or a reliable transport layer is implemented. The corresponding problems are then called PA-MEERR-L and PA-MEERR-T, respectively. Formally speaking, we consider the following problem:

   **Instance.** A directed graph \( G = (V, E) \) with link error probability \( E_{u,v}(p) \in [0, 1] \) that is function of transmitting power \( p(u, v) \). A value \( \kappa(u, v) \) specifies the maximum number of retransmissions implemented at the MAC layer by node u for every link \((u, v)\). Typically, this value is seven for IEEE 802.11 [13], [14].

   It is set to \( \infty \) if no such bound is set at the MAC layer. We are also given a pair of fixed source node s and destination node t.

   **Question.** Find a power \( p^*(u, v) \) for each link \((u, v)\) such that the minimum expected energy path connecting s and t consumes the least power among all possible power assignments. There are two scenarios here: either only link layer reliability is implemented, or transport layer reliability is implemented.

2. **Power assignment for single sink unicasts.** A power assignment that will produce the most energy efficient routing for a specific pair of source and target nodes does not mean that it will also produce the most energy efficient routing for all pairs of nodes. It is easy to show that no a single power assignment will consistently produce the most energy efficient unicast for all pairs of source and target nodes when the reliable transport layer is to be implemented. On the other hand, when a set of unicasts have the same target node (or equivalently have the same source node), we will show that we can find a unique power assignment such that it will produce the most energy efficient routing for all such unicasts. Formally, we consider the following problem:

   **Instance.** A directed graph \( G = (V, E) \) with link error probability \( E_{u,v}(p) \in [0, 1] \) that is function of transmitting power \( p(u, v) \). A value \( \kappa(u, v) \) specifies the maximum number of retransmissions for every link \((u, v)\). Fixed source node is s.

   **Question.** Find a power \( p^*(u, v) \) for each link \((u, v)\) such that the minimum expected energy path connecting s and any target node t consumes the least power among all possible power assignments.

3. **Power assignment for multipath unicast.** Multipath routing has been proposed to improve the reliability or the network throughout [4], [8], [15]. However, none of these specifically studied the minimum energy multipath routing in unreliable environment. Simple heuristics were given in [11] for minimum energy unicast using multipaths. In this paper, given source node s and target node t and a parameter k, we will present a polynomial time method to find the optimum power assignment and the disjoint k-paths connecting s and t such that the expected total energy is minimized. Specifically, we consider the following problem:

   **Instance.** A directed graph \( G = (V, E) \) with link error probability \( E_{u,v}(p) \in [0, 1] \) that is function of transmitting power \( p(u, v) \). A value \( \kappa(u, v) \) specifies the maximum number of retransmissions for every link \((u, v)\). Specified source node s and target node t. An integer k specifies the number of disjoint paths required from s to t.

   **Question.** Find a power \( p^*(u, v) \) for each link \((u, v)\) such that the minimum expected energy k-node-disjoint paths connecting s and target node t consumes the least power among all possible power assignments.

4. **Energy efficient multicast.** Multicast routing has been studied extensively in the literature [16], [17]. We then seek the optimum power assignment that
results in the minimum power consumption for multicast routing in the presence of unreliable links.

Instance. A directed graph $G = (V, E)$ with link error probability $\mathcal{E}_{u,v}(p)$ [0,1] that is a function of transmitting power $p(u,v)$. A value $\kappa(u,v)$ specifies the maximum number of retransmissions for every link $(u,v)$. Specified source node $s$ and a set of $k$ receivers $Q = \{q_1, q_2, ..., q_k\}$.

Question. Find a path $P^*(u,v)$ for each link $(u,v)$ and then find a tree $T$ that spans all the receivers in $Q$ such that $T$ has the minimum expected energy among all possible power assignments and all trees connecting $s$ and $Q$.

2.4 Expected Energy Consumption of a Path

Given a simple path $\Pi = v_{i_1}v_{i_2}...v_{i_k}$ connecting the source $s$ and the destination $t$, where $s = v_{i_1}$, $t = v_{i_k}$, we briefly show how to compute the expected energy consumption of this path under both models.

When a link-layer reliability is implemented, obviously, the expected power consumption of path $\Pi$ with link-layer reliability is

$$\mathcal{P}_l(\Pi) = \frac{1}{1 - \mathcal{E}_{v_{i_j},v_{i_{j+1}}}(p)} p(v_{i_j}, v_{i_{j+1}}).$$

Here, $1 - \mathcal{E}_{v_{i_j},v_{i_{j+1}}}(p)$ is the expected number of total retransmissions of link $(v_{i_j}, v_{i_{j+1}})$, including the initial transmission.

When a transport-layer reliability is implemented, let $\Pi_{i_{j-1}}$ be the subpath of $\Pi$ from node $s = v_{i_1}$ to node $v_{i_j}$. The expected power consumption of path $\Pi$ under transport-layer reliability model is then

$$\mathcal{P}_t(\Pi) = E(N(i_{k-1})), \left(\mathcal{P}_l(\Pi_{i_{k-1}}) + p(v_{i_k},v_{i_{k-1}})\right)$$

$$= \mathcal{P}_l(\Pi_{i_{k-1}}) + \frac{p(v_{i_k},v_{i_{k-1}})}{1 - \mathcal{E}_{v_{i_k},v_{i_{k-1}}}(p)}$$

$$= \sum_{j=2}^{k} \prod_{j=3}^{k} \left(1 - \mathcal{E}_{v_{i_{j-1}},v_{i_{j-2}}}(p)\right).$$

Here, $N(i_{k-1})$ denotes the number of transmissions performed by node $v_{i_{k-1}}$, and $E(N(i_{k-1}))$ is its expected value.

Let us see an example of computing the expected energy consumption of a path. Fig. 1 illustrates a network of six nodes, where the link successful delivery probabilities are shown along the edges. Assume that the node power by all nodes are equal, denoted as one unit here. When link layer reliability is implemented, the energy efficient path from $A$ to $F$ is then $ABCF$, and the total cost is $\frac{1}{17} + \frac{1}{17} + \frac{3}{17} = 3.47$. When the reliable transport-layer is implemented, for the same path $ABCF$, its expected energy cost becomes $\frac{1}{0.9} + \frac{0.8}{0.9} + \frac{1}{0.9} = 4.04$.

2.5 Related Work

As we mentioned, most existing energy efficient routing protocols [1], [2], [3], [4], [5] do not take into account the reliability of the wireless links and simply assume wireless links are reliable. Until recently, a number of routing protocols have been proposed to remedy the unreliability of the wireless channels. Basically, these protocols can be classified into the following classes:

Routing in reliable link layer implementation. De Couto et al. [18], based on experimental data, argued that routing protocols should consider the quality of the links on a path in order to reduce retransmission cost. They proposed a new routing metric, the expected number of transmission (ETX), which is the reverse of the probability of a successful transmission over a link. The end-to-end cost of a path is then defined as the sum of the ETX values of the links on the path; the routing protocol simply computes routes that minimize this cost. However, they did not consider the energy consumption. Banerjee and Misra [10] first studied the minimum energy routing under reliable link layer. For a link $(u,v)$, it is easy to see that the expected total power needed until there is one successful transmission from $u$ to $v$ is $P(u,v) = \frac{1}{1 - \mathcal{E}_{u,v}(p)}$. Thus, to find an energy efficient reliable path from $s$ to $t$ is equivalent to find the lowest cost path from $s$ to $t$ in a link weighted network $G = (V,E, P)$, where the weight for each link $(u,v)$ is the expected power $P(u,v)$ needed for one successful transmission. This clearly can be directly solved by Dijkstra’s algorithm [19] in a centralized manner and Bellman-Ford algorithm [19] in a distributed manner. Routing method proposed in [10] used such method.

Routing in reliable end-to-end implementation. When the reliable transport layer is used instead, the retransmission cost is different with above case, since when a packet drops, it induces retransmission on all preceding links that were successfully traversed prior to the drop. Jaklari et al. [12] introduced a new metric, the expected number of transmissions on a path (ETOP), which considers not only the quality of links but also the relative positions of the links on the path. However, their method does not consider the transmission energy. In [10], the authors first introduced the minimum energy routing problem with reliable transport layer and lossy links. However, they only proposed an approximate heuristic for this problem. Then, Dong et al. [11] proposed an energy efficient reliable routing when the power used by each link is already fixed. For completeness of presentation, we briefly reviewed their method here using our own word (illustrated by Algorithm 1). Assume that the simple path $v_{i_1}v_{i_2}...v_{i_{k-1}}v_{i_k}$ is the least cost path, where $s = v_{i_1}$, $t = v_{i_k}$. A key observation is that the path $v_{i_1}v_{i_2}...v_{i_{k-1}}$ also consumes the least expected total energy from $s = v_{i_1}$ to node $v_{i_{k-1}}$. Then, an algorithm similar to Dijkstra’s shortest path algorithm can be used to find the path with the least expected total energy [10]. Let $P(u)$ be the expected minimum power needed from the source node $s$ to a node $u$ in the network. Obviously, $P(s) = 0$ and Algorithm 1 to find the shortest path.
tree is straightforward. Here, $F(u)$ denotes the parent node of $u$ in the shortest path tree rooted at the source node $s$. It is easy to prove that whenever a node $u$ is added to the set $S$, the path defined by the transversal of nodes $u \rightarrow F(u) \rightarrow F(F(u)) \rightarrow \cdots \rightarrow s$ indeed has the minimum expected energy.

Algorithm 1. Centralized minimum expected energy and reliable unicost routing with reliable transport-layer cMEERR-T($G, s, p, E, F(), \mathcal{P}$).
1: for every node $v \in V$ do
2: $P(v) \leftarrow 0$, and $P(v) = \infty$.
3: end for
4: $P(s) \leftarrow 0$, $S \leftarrow \{s\}$, and $u \leftarrow s$.
5: while $S \neq V$ do
6: $\text{temp} \leftarrow \infty$;
7: for each node $v \notin S$ do
8: if $\frac{P(u)+P(v)}{1-\mathcal{E}_{u,v}(p)} < P(v)$ then
9: $F(v) \leftarrow u$, and $P(v) \leftarrow \min\{P(u)+P(v), P(v)\}$;
10: end if
11: end for
12: if $P(v) < \text{temp}$ then
13: $\text{temp} \leftarrow P(v)$, and $u \leftarrow v$;
14: end if
15: end for
16: $u \leftarrow u'$, and $S \leftarrow S \cup \{u\}$;
17: end while

In [11], the authors also proposed methods to find the energy efficient paths in the mixed retransmission model, where some links may provide partial reliable delivery while the others may not, and proved that a multipath problem is NP-hard. However, [10] and [11] only focus on energy efficient routing (MEERR), which aims to find the minimum expected energy path from the source to the destination. They assume that transmission powers and link errors are fixed at each link. In this paper, we treat link error rate as a certain function of the transmission power, then consider a joint problem of power assignment and energy efficient routing (PA-MEERR), which aims to find a power assignment and a corresponding path such that the total expected energy consumption is minimized.

3 RELIABLE ENERGY EFFICIENT UNICAST: POWER ASSIGNMENT AND ROUTING
3.1 Reliable Link Layer Implementation
For convenience, let $P_P(s, t)$ denote the minimum expected power from node $s$ to node $t$ when the power of each link $(u, v)$ is assigned by $p$. We first study how to dynamically adjust the transmission power of each link $(u, v)$ such that the expected power $P_P(s, t)$ is minimized among all possible power assignment methods $P$. Assume that the power assignment $P^*$ produces the optimum answer, and the simple path $v_1, v_2, \ldots, v_k$ is the least cost path, where $s = v_1$, $t = v_k$. Obviously, $P^*(s, t) = \sum_{i=1}^{k-1} \frac{P^*(v_i, v_{i+1})}{1-\mathcal{E}_{v_i,v_{i+1}}(P^*)}$.

Consequently, to find the optimum power assignment $P^*$, it is equivalent to find a power assignment for each link $(u, v)$ such that $\frac{P(u)}{1-\mathcal{E}_{u,v}(p)}$ is minimized by intelligently choosing $p$. This can clearly be solved optimally for each link based on Algorithm 2.

Algorithm 2. Centralized power assignment and minimum expected energy and reliable unicost routing with reliable link-layer cPA-MEERR-L($G, s, \mathcal{E}, p^*, F(), \mathcal{P}$).
1: for every node $v \in V$ do
2: $F(v) \leftarrow 0$, and $P(v) = \infty$.
3: end for
4: $P(s) \leftarrow 0$, $S \leftarrow \{s\}$, and $u \leftarrow s$.
5: while $S \neq V$ do
6: $\text{temp} \leftarrow \infty$;
7: for each node $v \notin S$ do
8: if $\frac{P(u)+P(v)}{1-\mathcal{E}_{u,v}(p^*)} < P(v)$ then
9: $F(v) \leftarrow u$, and $P(v) \leftarrow \min\{P(u)+P(v), P(v)\}$;
10: end if
11: end for
12: if $P(v) < \text{temp}$ then
13: $\text{temp} \leftarrow P(v)$, and $u \leftarrow v$;
14: end if
15: end for
16: $u \leftarrow u'$, and $S \leftarrow S \cup \{u\}$;
17: end while

Similarly, we can design a distributed method that is similar to Bellman-Ford [19] to find the optimum power assignment.

3.2 Reliable End-to-End Implementation
We are now ready to study how to assign an optimum power $P^*(s, t)$ to every link $(u, v)$ such that the expected energy consumption is minimized among all possible power assignments for all links. Observe that the least cost path of a routing depends on the power $p$ assigned to each link $(u, v)$, while on the other hand, to find the optimum power assignment $P^*$, we need to compute the least cost path from the source to the target under the optimum power assignment. In the following, we will present a novel approach to break this dependence cycle. Assume for the moment that we already have an optimum power assignment $P^*$. Consider the path $v_1, v_2, \ldots, v_k$ from $s$ to $t$ with the minimum expected total energy, where $s = v_1$, $t = v_k$. Notice that $P(s, v_k) = \frac{P(s, v_{k-1}) + P(v_{k-1}, v_k)}{1-\mathcal{E}_{v_{k-1},v_k}(P^*)}$.

Then, we clearly need to select a power level $P^*(v_{k-1}, v_k)$ such that $\frac{P(s, v_{k-1}) + P^*(v_{k-1}, v_k)}{1-\mathcal{E}_{v_{k-1},v_k}(P^*)}$ is minimized when $P(s, v_{k-1})$ is known. We thus have the following power assignment algorithm (Algorithm 3) for minimizing the expected energy consumption from a source node $s$ to any given node $v$. We assume that the link error probability function $\mathcal{E}_{u,v}(p)$ (i.e., its dependence on the transmission power $p$) is already known for each link $(u, v)$ in the network.
Algorithm 3. Centralized power assignment and minimum expected energy and reliable unicast routing with reliable transport-layer cPA-MEERR-T(G, s, E, p*, F(), P).
1: for every node v ∈ V do
2:     \( F(v) \)---\( \emptyset \), and \( P(v) = \infty \).
3: end for
4: \( P(s) \)---0, \( S \)---\{s\}, and \( u \)---s.
5: while \( S \neq V \) do
6:     \( \text{temp} \)---\( \infty \).
7:     for each node \( v \notin S \) do
8:         Find the optimum power \( p^*(u, v) \) that minimizes \( \frac{1}{\gamma_{e, \alpha, v}(p)} \) among all possible power assignments \( p(u, v) \) for link \( (u, v) \).
9:         if \( \frac{1}{\gamma_{e, \alpha, v}(p)} < P(v) \) then
10:             if \( P(v) < \text{temp} \) then
11:                 \( \text{temp} \)---\( P(v) \), and \( u \)---v.
12:             end if
13:         end if
14:     end for
15:     \( u \)---u', and \( S \)---\( S \cup \{u\} \).
16: end while

For Algorithm 3, we then prove the following theorem:

**Theorem 1.** The power assignment \( p^* \) computed by Algorithm 3 is indeed optimum, and the path tree traversed based on \( F() \) indeed gives the shortest path tree rooted at the source node \( s \).

**Proof.** We prove this by using induction on all nodes in \( V \).

Without loss of generality, assume that we add nodes \( v_1 = s, v_2, \ldots, v_{n-1}, v_n \) to \( S \) in this order. It is easy to show that the link \( (s, v_2) \) consumes the least expected energy among all paths connecting \( s \) and \( v_2 \). Assume that the statement is true for all nodes \( v_1, v_2, \ldots, v_k \), i.e., the path found by Algorithm 3 using the corresponding power assignment consumes the least expected energy among all power assignments. For all other nodes, let \( u \) be the node such that its precedent node in the path, which consumes the least expected energy, is some \( v_i \) with \( 1 \leq i \leq k \). Then, clearly, the path from \( s \) to \( v_i \) must consume the least expected power, i.e., \( P(v_i) \). Since the expected power from \( s \) to \( u \) along the optimal path is \( \frac{1}{\gamma_{e, \alpha, v}(p)} \). Algorithm 3 indeed finds the correct node \( u \) and the correct power assignment \( p \). \( \Box \)

We then show how to implement it in a distributed manner. Assume that each node \( v \) stores a variable \( P(s, v) \) that denotes the expected power from source node \( s \) to node \( v \) of the best known path so far. Algorithm 4 then illustrates our distributed method of finding the optimum power assignment and also the route from \( s \) to any node \( v \) in the network. Notice that out-neighbors of a node \( v \) in \( G \) are nodes that can receive the signal sent from \( v \) directly when \( v \) transmits at the maximum power. It is difficult to prove that this distributed method will terminate after at most \( n \) rounds, and it will produce a correct answer.

**Algorithm 4.** Distributed power assignment and minimum expected energy and reliable unicast routing with reliable transport-layer dPA-MEERR-T(G, s, E, p*, F(), P) at node \( v \)
1: \( F(v) \)---\( \emptyset \), \( P(s, v) = \infty \) and \( \text{temp}(u, v) \)---\( \infty \).
2: if \( v = s \), then \( P(s, s) = 0 \) and sends a message to all its out-neighbors in \( G \) informing a new \( P(s, v) = 0 \).
3: while received a message from incoming neighbor \( u \) updating \( P(u, v) \) do
4:     Find the optimum power \( p^*(u, v) \) that minimizes \( \frac{1}{\gamma_{e, \alpha, u}(p)} \) among all possible power assignments \( p(u, v) \) for link \( (u, v) \).
5:     if \( \frac{1}{\gamma_{e, \alpha, v}(p)} < P(v) \) then
6:         \( F(v) \)---u, and \( P(v) = \frac{1}{\gamma_{e, \alpha, v}(p)} \).
7:     Node \( v \) records \( \text{temp}(u, v) \)---\( p^*(u, v) \);
8:     Node \( v \) sends a message to its out-neighbors informing its new \( P(s, v) \).
9: end if
10: end while
11: Node \( F(v) \) is the parent node of \( v \) in the minimum expected energy path tree rooted at \( s \), \( \text{temp}(u, v) \) is the final optimum power assignment \( p^*(u, v) \).

### 3.3 Mixed Reliability Implementations

When some links in the wireless networks implement a link layer reliability, the power assignment algorithm should be modified to accommodate this accordingly. The previous algorithms are motivated and designed for the pure end-to-end retransmission model, i.e., assuming the MAC layer does not provide any retransmission mechanism. Notice that in practice, some links may already provide the link reliability to some extent. A simple modification of the above algorithm will enable it to solve the mixed retransmission model. When a link \( (u, v) \) already provides the link layer reliability, we modify the link power and the link error probability as follows:

\[
\bar{p}(u, v) = \frac{p(u, v)}{1 - E_{e,v}(p)}, \quad \text{and} \quad E_{e,v}(\bar{p}) = 0.
\]

When a link \( (u, v) \) does not provide the link layer reliability, we simply let \( \bar{p}(u, v) = p(u, v) \) and \( E_{e,v}(\bar{p}) = E_{e,v}(p) \). We can then call cMEER-T(G, s, \bar{p}, E, F(), P) to find the minimum expected energy path from the source node \( s \) to all other nodes in \( V \), and cPA-MEERR-T(G, s, \bar{p}, F(), P) (or dPA-MEERR-T(G, s, E, p*, F(), P)) to find the best power assignment. Notice that we will replace \( p \) in all algorithms with \( \bar{p} \) whenever it is used.

### 3.4 Bounded Retransmission Times

In previous discussions of implementing link layer reliability, we assume that a node \( u \) will retransmit the frame until it is received by the other end node \( v \) regardless the number of existing retransmissions of the frame. In practice, link layer technologies such as the 802.11 MAC protocol typically make a bounded number of retransmission attempts for a lost or corrupted frame. Further, losses can be recovered through end-to-end retransmissions. Thus, we generally assume that for each link \( (u, v) \), there is an integer \( \kappa(u, v) \) that specifies the maximum number of retransmissions (including the initial transmission) for a lost or corrupted frame. When a link \( (u, v) \) does not pose such limit, we simply set \( \kappa(u, v) = \infty \). If a link \( (u, v) \) does not implement link layer reliability, we can simply set \( \kappa(u, v) = 1 \). Obviously, we need to design transport-layer
retransmission to guarantee the end-to-end reliability. We then modify the link power and the link error probability as follows:

\[
\tilde{p}(u, v) = p(u, v) \cdot \min \left\{ \frac{1}{1 - E_{u,v}(p)}, \kappa(u, v) \right\},
\]

\[
\bar{E}_{u,v}(\tilde{p}) = E_{u,v}(p) \min \left\{ \frac{1}{\max \kappa(u, v)} \right\}.
\]

We can then call algorithm cMEERR-T\((G, s, \tilde{p}, \bar{E}, F(), \mathcal{P})\) to find the minimum expected energy path from the source node \(s\) to all other nodes in \(V\) and algorithm cPA-MEERR-T\((G, s, \tilde{E}, \bar{E}, \bar{p}, F(), \mathcal{P})\) to find the optimum power assignment for minimum expected energy routing.

### 3.5 Single Sink Multiple Unicasts

It is easy to show that there is no a single power assignment that will consistently produce the most energy efficient unicast for all pairs of source and target nodes. Fortunately, in many application scenarios, the communications often have a common source node or a common target node, e.g., there is a common sink node in the data collection communications in wireless sensor networks. Thus, we study how to set the transmission power for each individual link that is globally applicable for every unicast communication when there are many simultaneous unicasts with the same sink or source. In other words, the single power assignment will produce the unicast paths with the least expected energy consumptions. Our algorithm is exactly the same as cPA-MEERR-T\((G, s, \tilde{E}, \bar{E}, \bar{p}, F(), \mathcal{P})\) (or dPA-MEERR-T\((G, s, \tilde{E}, \bar{E}, \bar{p}, F(), \mathcal{P})\)), where \(s\) is the common source node. The proof of the correctness is straightforward. Notice that when only the link layer reliability is implemented, Algorithm 2 also gives the optimal power assignment for any set of unicasts. However, when the transport layer reliability is implemented, Algorithm 3 does not necessarily produce the optimal power assignment for an arbitrary set of unicasts.

### 4 Multipaths Energy Efficient Unicast

Traditionally, when we need to send a data from a source node to the target node, often a path is used for routing. However, recent study [11] showed that multipath routing may both improve reliability and reduce energy consumption. In this section, we study how to find \(k\) node-disjoint paths between the source node and the target node with the minimum expected energy. We will present centralized method (Algorithm 5) to solve it optimally. Notice that since the paths are node-disjoint (except the source node and the target node), except the power used by the source node \(s\), the power used by any other node on a path, say, \(u\), is used to reach exactly one next-hop node. Thus, if we fix the power level of the source node \(s\) as \(p_s\), then the problem becomes finding \(k\) node disjoint paths with minimum total expected link energy consumption when we set the cost of every link \((s, u)\) as 0 for link \((s, u)\) with \(p(s, u) \leq p\). By checking all possible power levels for the source node, we will find the optimum \(k\)-node disjoint paths for routing.

3. There are at most \(d_i - k + 1\) power levels to check where \(d_i\) is the total out-neighbors of node \(s\).

#### Algorithm 5: Minimum expected energy and reliable \(k\)-disjoint multipath routing with reliable link-layer MEERMpR-L\((G, s, t, k, p, \mathcal{E})\).

1. Assume that the power levels of source node \(s\) to its \(d\) neighbors \(v_1, v_2, \ldots, v_d\) are \(p_1 \leq p_2 \leq \cdots \leq p_d\), where \(d \geq k\). Let \(P = \infty\).
2. for \(i = k\) to \(d\) do
3. Assume source node \(s\) uses power \(p_i\). Node \(s\) can communicate with all nodes \(v_1, v_2, \ldots, v_i\) using power \(p_i\). Let \(p'_i = \frac{p(s, v_i)}{1 - \frac{1}{\kappa(s, v_i)}}\).
4. Assume the link cost of each link \((s, v_j)\), for \(1 \leq j \leq i\), is 0. The cost of each other link \((u, v)\) is \(\frac{p(s, v)}{1 - \frac{1}{\kappa(u, v)}}\). Find \(k\) internal-node disjoint paths \(\Pi_i\) from \(s\) to \(t\) with the minimum total link costs \(\delta_i\).
5. If \(\delta_i + p'_i < P\), then \(P = \delta_i + p'_i\), \(\ell = i\), and the current best \(k\)-internal-node disjoint paths \(\Pi_i\) is \(\Pi_i\).
6. end for
7. Source node \(s\) transmits at power \(p_i\) and the optimum \(k\)-disjoint path is \(\Pi_i\).

As discussed in [11], multipath routing could use another more general directed subgraph, say, \(H\), rooted at the source node \(s\), has the target node \(t\) as its only leaf node. If a node \(u\) relays the data from the source, potentially, all its downstream children in \(H\) could receive the data. Since the links are unreliable, some (or none) of its downstream children receive the data correctly. Then, these nodes receive the data correctly continue to relay the data to their downstream children nodes. When the target node gets the data, it sends an acknowledge message back to the source node. As always, we can assume that the ACK is not lost here for the simplicity of analysis. The source node will restart the transmission if no ACK is received. The objective is to find a directed graph \(H\) such that the expected power consumption of unicast over \(H\) is minimum among all directed graphs rooted at \(s\) and having \(t\) as its leave node. This problem is much harder. We leave this as future work to find such structure and its corresponding optimum power assignment.

### 5 Overlay-Based Multicast

In this section, we study the multicast when the one-to-one communication model is used by all nodes. In implementing a multicast based on a tree \(T\) with unreliable links, assume that, for an internal node \(u \in T\), there are several children nodes, say, \(v_1, v_2, \ldots, v_k\). Node \(u\) needs to send the data to all its children nodes. There are two possible implementation approaches here: one-to-one communication model or one-to-all communication model. In the one-to-one communication model, node \(u\) sends the data individually to each of its children and will use the power that is the most energy efficient to reach that node. For example, it may first send the data to child \(v_1\) until it received the data correctly; it then sends the data to node \(v_2\), and so on. We assume that node \(u\) will adjust its power based on the receiving node \(v_i\), i.e., the power used to send data to different nodes \(v_i\) may be different here. In the one-to-all communication model, node \(u\) can send the data to all its children. However, it is hard to model such communication model using the single link error probability. Thus, here we only present our results on one-to-one communication model.

Consider any directed link \((u, v)\) in the tree \(T\). Let variable \(N(u, v)\) be the number of transmissions from
node $u$ to node $v$ by a specific multicast transmission from the source node $s$ to the target nodes. The total power consumption of tree $T$ is $\sum_{(u,v)\in T} N(u,v) \cdot p(u,v)$. The expected power consumption of tree $T$ under one-to-one communication model is

$$P(T) = \sum_{(u,v)\in T} E(N(u,v)) \cdot p(u,v) = \sum_{(u,v)\in T} \frac{p(u,v)}{1 - \epsilon_{u,v}(p)}.$$  

Thus, given the power assignment for each communication link $(u,v)$, finding the multicast tree with the least expected energy consumption is the standard Steiner tree problem, where the weight of each link $(u,v)$ is $\sum_{(u,v)\in T} \frac{p(u,v)}{1 - \epsilon_{u,v}(p)}$. This problem is well-known to be NP-hard [20]. It is straightforward that Algorithm 6 finds a multicast tree, whose expected energy consumption is no more than twice of the optimum. Here, $Q = \{q_1, q_2, \ldots, q_k\}$ is the set of receivers and the source node.

**Algorithm 6.** Minimum expected energy and reliable multicast routing with reliable link-layer MEERR-mediated local network $L(G, Q, p, E)$.

1. Find the path connecting every pair of nodes $q_i$ and $q_j$ that consumes the least expected energy under a given power assignment $p$ and the link error probability $\epsilon$.
2. Let $c(q_i, q_j)$ be the expected energy consumption of the found path connecting $q_i$ and $q_j$. Let $H$ be the overlay network over $Q$, where the cost of each virtual link $(q_i, q_j)$ is $c(q_i, q_j)$.
3. Find the minimum spanning tree $T$ of $H$. All physical links of the selected virtual link $(q_i, q_j) \in T$ form the final multicast tree.

When we need to assign the power to each link to minimize the expected power consumption of the multicast, it is not straightforward that it will directly imply a constant approximation method by using Algorithm 2 instead in the first step of Algorithm 6. The reason is that the power assignment of Algorithm 2 works correctly only if we have a common source node (or target node) for some unicasts. The optimal power assignments for different unicasts may be conflicted with each other when they have different source and target nodes. We leave the approximation of optimal power assignment for multicast as our future work.

### 6 Simulation Study

#### 6.1 Simulation Settings and Implementation

We conducted extensive simulations to study the performances of the proposed protocols. We use Qualnet 3.7 [21] in RH Linux 9.0 to run our simulations. We adopt the TWO-RAY path loss model and the Additive White Gaussian Noise model, and the noise factor is 10. The interference is calculated as the sum of all signals on the channel. The physical layer model we adopted in the simulation is PHY802.11b with 2 Mbps data rate. Other than SINR threshold, signal reception model is BER based.

We implement the distributed power assignment and minimum expected energy and reliable routing (dPA-MEERR) protocol (including dPA-MEERR-L and dPA-MEERR-T) in Qualnet. Both dPA-MEERR-L and dPA-MEERR-T are based on a modified Bellman-Ford, but they do not take counts of hop as distance from source to destination. Instead, they first assign optimal transmission power for each link and then take the expected power needed for one successful transmission as distance from source to destination. We then evaluate the performance of dPA-MEERR in random networks and compare the performance of dPA-MEERR with existing distributed routing protocols, which include the Bellman-Ford protocol that does not specifically take the energy efficiency into consideration and the protocol GAMER described in [11] that considers the unreliability of the wireless links but without the dynamic power assignment. For the Bellman-Ford method, we implement a modified version because the traditional Bellman-Ford protocol will not adjust transmission power, and it is incomparable with dPA-MEERR. After Bellman-Ford algorithm is used to find a path with the minimum number of hops from the source node to the target node, the modified version adjusts the transmission power of every link $(u,v)$ on the path to the optimum power $p$ that minimizes the expected power consumption over this link $(u,v)$. In our implementation of GAMER protocol, we use a more realistic model: the power of a link $(u,v)$ is set proportional to $\|uv\|^\alpha$, as in [11], but the link error probability is based on the BER table provided in Qualnet instead of being randomly selected in [11]. To implement all these methods, we also make the following changes in Qualnet: 1) We modify the packet structure of Qualnet so that we can store more information in the routing table for dPA-MEERR to enable dynamic assigning power and using the assigned power for packet transmission in the physical layer. 2) We need get the signal propagation information of a link in the period of establishing routing table. It includes transmission power (TxPower) of the source who sends the routing message, and receiving power (RxPower) of current node who receives the routing message, and SINR. We then attach these information to the received message in the physical layer and deliver it to dPA-MEERR that is in the network layer. Using these information, dPA-MEERR can compute the optimal transmission power for the link between source node and current node. 3) We need adjust the transmission power of the data packets (not control packets) to ensure energy efficiency. Because we cannot set the transmission power of the data packet to the optimal in network layer, we attach the optimal transmission power, which is retrieved from the routing table of dPA-MEERR, to the data packet to be delivered to physical layer. Physical layer checks whether the data packet carries the optimal transmission power. If yes, physical layer then transmits this packet using the optimal transmission power; otherwise, it transmits the data packet with default power. All the broadcast messages are transmitted with default power.

We use CBR to evaluate the performance of dPA-MEERR-L and FTP to evaluation performance of dPA-MEERR-T, since CBR adopts unreliable UDP as its transport layer, while FTP adopts reliable TCP as its transport layer. The packet sizes of both CBR and FTP are 512 bytes. The start time of them is 10 seconds, and all traffics last for 1,000 seconds. The interval of CBR is 1 second. The maximum transmission power of all nodes is set as 15.0 dBm, and the receiver sensitivity is set as $-89.0$ dBm [22]. The retransmission times for short packets are at most 4 and are at most 7 for long packets in the link layer [13], [14].

We study the performances of various protocols using the following metrics:
1. **End-to-end delay.** Time to send a packet from source to destination.
2. **Throughput.** Bytes successfully transmitted from source to destination per second.
3. **Average path energy consumed per packet.** Average energy consumed to transmit a packet to destination along the path established by different routing protocols. The first two metrics represent the quality of service provided by routing methods, while the third metric represents energy efficiency of routing methods.

For random networks, we randomly generate $n$ nodes, where $n \in [20, 100]$. The coordinates of the wireless nodes are uniformly and randomly distributed in a square region of 1,000 meters by 1,000 meters. We repeated 10 simulations with different seeds for each scenario with $n$ nodes placed.

### 6.2 Routing Single Traffic in Random Networks

In our first simulation, we study the performance of several routing protocols in random networks when there is only single traffic in the network. Given a network deployment, we first randomly generate the source node and the target node for traffic. We then run three different routing protocols (modified Bellman-Ford, protocol GAMER proposed in [11], and our dPA-MEERR protocol) to test their respective performances. To study the performances of various protocols for random networks or different sizes, we always normalize the performance of each protocol by using the performance of modified Bellman-Ford protocol as the denominator. Thus, the performance of modified Bellman-Ford protocol is always treated as one.

Fig. 2 illustrates the energy consumption differences by different routing schemes when only the reliable link layer is implemented, and the network only has a single CBR traffic. For a network of $n$ nodes, we run 10 simulations, where a flow request is generated randomly. Given the network topology and flow request, we first compute the expected energy consumption of a routing path used by a certain routing method (Bellman-Ford, GAMER, or dPA-MEERR-L). Figs. 2a and 2b show the results. Here, Fig. 2b is the normalized average values by using Bellman-Ford’s result. Figs. 2c and 2d then give the real measurements of the actual power consumption used by different routing in the simulator. Clearly, both GAMER protocol [11] and our dPA-MEERR-L protocol consume much less energy than the modified Bellman-Ford method. The reducing of energy is more significant when the network becomes dense. This is because both GAMER and dPA-MEERR-L protocol tends to use short links, which results in smaller energy consumption, while Bellman-Ford protocol tends to use longer links, which results in large energy consumption due to more retransmissions caused by fragile long links and each transmission uses more power. Performances of dPA-MEERR-L and GAMEER are more stable than Bellman-Ford with different node layouts. Expected performance of dPA-MEERR-L in energy efficiency is obviously better than GAMER. Our protocol saves about 10 percent power consumption when the network is sparse.

We also conducted simulations to study the performances of different protocols when there is a single FTP traffic. Fig. 3 shows a clear advantage of dPA-MEERR-T over GAMER in energy consumption in both simulations and computed theoretical expectation values. The conclusion is similar with the case of reliable link layer.

Figs. 4a and 4b illustrate the evaluated (and normalized) end-to-end delay of CBR traffics by simulations when only reliable link layer is implemented. As expected, both GAMER and dPA-MEERR have larger delay than the modified Bellman-Ford protocol since they tend to use short links. The delay degradation becomes more significant when the network density increases. The delay of proposed dPA-MEERR protocol is about 10 percent to 20 percent smaller...
than that of the GMAER protocol. Figs. 4c and 4d illustrate the evaluated (and normalized evaluated) network throughput of FTP traffics when reliable transport layer is implemented. Since both GAMER protocol and our dPA-MEERR protocol use short links, the network throughputs achieved by these two protocols are smaller than that achieved by the modified Bellman-Ford method. In the worst case, the throughput achieved by the GAMER protocol is only about 5 percent of that of modified Bellman-Ford method. In this scenario, our protocol achieves a throughput at least twice of the throughput achieved by the GAMER in most networks. The improvement of dPA-MEERR over GAMER is more significant when the network becomes dense. In summary, dPA-MEERR has better performance on the end-to-end delay and throughput than GAMER.

6.3 Routing Multitraffics in Random Networks

In our second set of simulations, we study the performance of several routing protocols in random networks when there are several simultaneous traffics in the network. In the results reported later, we run three simultaneous traffics (either all

Fig. 3. Comparison of energy efficiency with reliable transport layer. (a) Expected energy. (b) Normalized expected energy. (c) Experimental energy. (d) Normalized experimental energy.

Fig. 4. Comparison of end-to-end delay and throughput. (a) Delay. (b) Normalized delay. (c) Throughput. (d) Normalized throughput.
CBR traffics or all FTP traffics). We test three different routing protocols (modified Bellman-Ford, protocol GAMER proposed in [11], and our dPA-MEERR protocol) to measure their respective performances. Again, we always normalize the performance of each protocol by using the performance of modified Bellman-Ford protocol as the denominator.

Fig. 5 illustrates the expected energy consumed for sending one packet from the source node to the target node when only reliable link layer is implemented. Similar to the single traffic case, both GAMER protocol [11] and our dPA-MEERR-L protocol consume much less energy than the modified Bellman-Ford method. The reducing of energy is more significant when the network becomes dense. The saving of our protocol compared with the GAMER protocol is not as significant as the single traffic case. The protocol proposed in this paper could save about 10 percent power consumption when the networks are sparse. Fig. 6 shows that both expected and evaluated transmission power of dPA-MEERR-T are less than GAMER when only the reliable transport layer is implemented.

Fig. 5. Comparison of energy efficiency with reliable link layer. (a) Expected energy. (b) Normalized expected energy. (c) Evaluated energy. (d) Normalized evaluated energy.

Fig. 6. Comparison of energy efficiency with reliable transport layer. (a) Expected energy. (b) Normalized expected energy. (c) Evaluated energy. (d) Normalized evaluated energy.
Figs. 7a and 7b illustrate the expected end-to-end delay for sending one packet from the source node to the target node using CBR when only reliable link layer is implemented. As expected, both GAMER protocol and our dPA-MEERR protocol use short links, the network throughputs achieved by these two protocols are smaller than that achieved by the modified Bellman-Ford method. In the worst case, the throughput achieved by the GAMER protocol is only about 5 percent of that of modified Bellman-Ford method. Observe that our protocol always achieves a throughput much larger than the previous GAMER protocol. On the average, the proposed dPA-MEERR protocol achieves a throughput about 3 to 4 times of the throughput achieved by GAMER protocol. In one example, the throughput achieved by dPA-MEERR protocol is about 5 times of the throughput achieved by GAMER protocol.

6.4 Practical Improvement

When we implement the minimum energy routing, we can do further improvement as follows: When a node \( u \) is sending a message to next-hop node \( v \) on the minimum expected energy path, the following scenario may happen: node \( v \) did not receive it due to link error, but another node \( w \) (here, node \( w \) could be not on the path from \( s \) to \( t \)) gets the data correctly. Then, a question to ask is: “should we stick to resend to node \( v \), or should we switch to node \( w \) by letting \( w \) forward the message instead.” We give a criterion when we should switch, i.e., the node \( w \) could start to forward the data now. Assume that the link layer reliability is implemented. Then, node \( u \) lets node \( w \) to do so when \( P(w,t) < P(u,t) \). This simple modification will decrease the expected energy consumption of the path. This is because the retransmission times from node \( u \) to node \( v \), which is a geometry distribution, is memoryless: for node \( v \) to get the data, the expected number of “new” retransmissions does not depend on the existed retransmissions from \( u \) to \( v \). In other words, we still need on the average \( \frac{1}{2} \) transmissions to send the message from \( u \) to \( v \), although at the moment we know that a number of transmissions already occurred from \( u \) to \( v \). If there are multiple such nodes \( w \) that got the data from node \( u \), we choose the one with the smallest expected path power consumption to the destination. The detailed implementation will be similar to the ExOR routing in [23] with the following differences. In the approach taken by ExOR protocol [23], a node \( w \) will forward the data packet if it has the smallest ETX value (expected transmission count) to the destination. In our approach, we use the expected total power consumption as the metric instead of ETX to order the neighboring nodes of a sender \( u \). Furthermore, in our approach, we will choose the sender \( u \) to resend the data, instead of letting a neighboring node \( w \) that received packets from \( u \) to relay the data packets for \( u \) when the expected path cost from \( w \) to destination is higher than that the expected path cost from \( u \) to the destination. Let’s illustrate this by an example shown in Fig. 8. When node \( B \) sends some data with destination \( F \). Assume that in some scenario, only node \( D \) got the data. Then, node \( D \) will not forward the data for node \( B \) since it has a higher expected cost to the destination \( F \). Notice that node \( D \) will forward the data if protocol ExOR [23] is used. On the other hand, when node \( D \) wants to send data to destination node \( F \).
Assume that only node B and A got the data (nodes E and C did not receive it correctly). Then, node B will forward the data for node D although it is not on the most energy efficient path from D to F. By adopting this strategy, we can prove that it will save energy compared with sticking to the precomputed path, i.e., DEF.

When the reliable transport layer is implemented, it is little bit trickier than the case when the reliable link layer is implemented. When one neighboring node (not the next-hop node) w successfully received the signal from the sender u, it does not mean that it will also quickly got the data next time when u has to perform retransmission due to the errors from downstream links. We can show that actually, in this case, we do need to stick to the path computed by Algorithm 1.

7 Conclusion

A number of energy efficient routing and power assignment protocols have been proposed in the literature. However, none of these protocols systematically studies the integration of power assignment and energy efficient routing with unreliable wireless links. In this paper, we proposed several power assignment and routing protocols and performed extensive simulations to study the performance of our unicast routing protocols. When there is only one common source node, we show that our power assignment and routing are optimal. We also presented a multicast routing protocol whose energy consumption is no more than two times of the minimum in a one-to-one communication model. In summary, all proposed schemes can efficiently save energy by finding optimal (or near optimal) power assignments and communication routes such that the expected total energy consumption is minimized. These proposed schemes can be widely used for various communication scenarios, i.e., unicast (with reliable link layer or transport layer), multipath routing, or multicast routing.

There are several challenging questions left for further study. First of all, in some applications, the unicast routings do not have a common source node (or target node). Then, it is an open problem whether we can find a uniform power assignment that is approximately good for all unicasts using reliable transport layer. Second, we showed how to find energy-efficient multipath routing and power assignment for unicast. We leave it as a future work to find a general structure that supports the power efficient routing by relaxing the disjointness requirement of the disjoint multipath routing. Third, we gave a power assignment and multicast routing protocol for one-to-one communication model whose energy consumption is no more than two times of the optimum. It is interesting to design a power assignment and multicast routing protocol when one-to-all communication model is used. Fourth, in our theoretical study, we assume that the link error probability is a function of the transmission power by fixing other parameters. It is unknown how to take the interference caused by the transmission of other nodes into the consideration. Last but not the least, we would like to design a power assignment strategy such that it is efficient for a mobile networks, i.e., the power assignment needs to take the possible future movement of neighbors into account.

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