Chapter 1

Survey on Link Quality Models in Wireless Ad Hoc Networks

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Emerging advanced wireless ad hoc networks make it possible for network resources to be utilized anywhere and anytime. However, compared with traditional infrastructure-based networks, wireless ad hoc networks are relatively unstable and unreliable due to the underlying wireless medium and infrastructureless nature. Existing techniques compensate for the instability of wireless links by employing either packet retransmissions, network coding, opportunistic routing, thick (or multiple) paths, or route fixes (using alternative routes). This chapter seeks to compare these techniques in terms of energy cost, the increment of reliability, and various other metrics.

Keywords: Energy; link quality; reliability; wireless ad hoc networks; wireless sensor networks.

1.1. Introduction

Existing protocols proposed for wireless ad hoc/sensor networks (e.g. Refs. 21, 22, 36, 37) are mostly designed based on an ideal spherical pattern of wireless links, where perfect reception within a particular range is assumed (i.e. packet transmission is 100% reliable). However, several empirical studies[6, 15, 33, 38] on the Berkeley mote platform have shown that the coverage of a node is irregular (i.e. the radio range varies significantly in different directions), and the packet loss also varies in different directions. Therefore, the assumption of perfect reception within a particular range is unrealistic and hence may result in non-ideal performance.

The performance may improve by excluding low-quality wireless links. However, such a strategy is insufficient and recent studies[30, 33, 38, 40] have shown that the quality of communication links has a significant impact on the performance of wireless ad hoc/sensor networks, including network lifetime, network throughput, resource usage, and reliability. Thusly, link quality should be considered as a critical dimension in the design space for wireless ad hoc/sensor networks, as pointed out in Refs. 14 and 30.

The accurate measurement of link quality is very important when taking link quality in the design space of wireless ad hoc/sensor networks into account. The research results on measuring wireless link quality and patterns[6,7,10,15,26,39,41] in wireless ad hoc/sensor networks have demonstrated that the communication range of a sensor node varies temporally and spatially due to a number of factors (e.g. the varying environments where sensor networks are deployed, unreliable wireless communications, and irregular radio patterns).

Woo *et al.*[32,33] model the link quality between a pair of sensor nodes as a statistical function over time. In their model,[32,33] a sensor node is able to extract the trend of link quality changes over time by tracking the packets heard/overheard, and it can use the tracked information to estimate future link quality. Xu and Li[34] study the link quality of wireless sensor nodes by exploiting the spatial correlation in links. The intuition behind spatial correlation is that sensor nodes that are geographically close to each other may have correlated link quality. Xu and Li[34] propose a weighted regression algorithm that allows each sensor node to capture the spatial correlation in the quality of its links.

An increasing number of works have begun to model link quality and utilize it for various applications. The existence of lower quality links incurs a low packet delivery ratio, hence reducing the performance of wireless ad hoc networks.[7,38] A common fault-tolerant technique is redundancy, such as retransmissions or erasure coding. Banerjee and Misra[3] model the link cost as a function of energy consumption for a single transmission attempt across the link and the link error rate, and propose several retransmission-aware routing schemes. Banerjee *et al.*[13] extend this work by relaxing the assumption of perfect reliability (zero error rate) in the link layer. Li and Shu *et al.*[24] further extend the result[13] by integrating power control techniques into the routing problem proposed in Ref. 13.

In Ref. 25, we consider the unicast routing problem in wireless ad hoc networks with unreliable links in scenarios featuring bounded retransmission times at the link layer. We model a wireless ad hoc network as a market and introduce the concept of benefit, adopting this concept to reflect the importance of a packet. The benefit is used to balance the maximization of the packet delivery ratio and the minimization of effective energy consumption.

Kwon *et al.*[23] propose a network lifetime maximization problem under reliability constraints in wireless sensor networks. The authors first propose a retry limit allocation problem similar to the quota assignment problem.[25] They[23] propose a greedy solution to this problem. Similar to Ref. 13, Misra and Banerjee[27] model the link energy-cost as a function of energy consumption for a single transmission attempt across the link and the link error rate; however, their objective is to find the best route with the greatest residual lifetime.

Opportunistic routing[4] utilizes redundancy in omnidirectional transmissions to make up for packet loss over lossy links. Intuitively, wireless channels between a pair of nodes change over time, but if there are multiple receivers for a sender, then the probability of successful delivery will likely increase.

Besides retransmissions, network coding can also be employed to reduce the effect of lower quality links. Certain network coding methods use replication (redundancy) to send identical copies of a message simultaneously over multiple paths in an effort to mitigate the effects of a single path failure.[31] Jain *et al.*[20] apply erasure coding to delay tolerant networks (DTNs). Cui *et al.*[12] propose a jointly opportunistic source coding and opportunistic routing (OSCOR) protocol for correlated data gathering in wireless sensor networks. Cristescu and Beferull-Lozano[11] consider a sensor network that measures correlated data, where the task is to gather all data from the network nodes to a sink.

1.2. Background

Existing techniques that improve routing reliability can be classified as retransmissions, network coding, multiple paths, and alternative paths. Each of the four categories can be further classified into sub-categories as shown in Figure 1.1.

Retransmission methods can be further classified into three categories as follows: (1) Hop-by-hop retransmission: A path is chosen from source to sink, and an automatic repeat request (ARQ) is used at the link layer to request the retransmission of packets lost on every link in the path. (2) End-to-end retransmission: A path is chosen from source to sink, and packets are acknowledged by the sink, or destination node. If the acknowledgment for a packet is not received by the source,

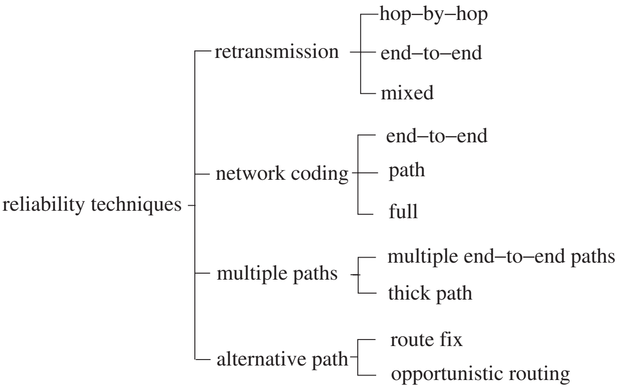

Fig. 1.1. The classification of existing techniques that can improve routing reliability.

the packet is retransmitted. (3) Mixed retransmission: Links on a path may or may not provide hop-by-hop retransmission, while end-to-end retransmission is provided at the transportation layer.

Most existing works[3, 13, 24, 25] consider both hop-by-hop and end-to-end retransmissions. Some[9] consider only hop-by-hop retransmissions. Reference 13 further takes mixed retransmission into account.

Network coding can be classified into three sub-categories: (1) End-to-end coding: A path is chosen from source to sink, and an end-to-end forward error correction (FEC) code, such as the Reed-Solomon code, LT code, or Raptor code, is used to correct packets that become lost between source and sink. (2) Path coding: A path is chosen from source to sink, and every node on the path employs coding to correct lost packets. The most straightforward way of doing this is for each node to use one of the FEC codes for end-to-end coding, decoding, and re-encoding the packets it receives. (3) Full coding: In this case, paths are eschewed altogether. A subgraph that specifies the frequency with which every node transmits packets is chosen, and the random linear coding scheme is used.

By providing multiple paths from source to destination, multiple-path techniques can improve the bandwidth of data transmission between the source-destination pair. Two techniques are classified under this category: multiple end-to-end paths and a thick path.

The classification of link-quality-based, constraint-free routing models based on the underlying techniques is illustrated in Figure 1.1. Besides this classification, constraint-free routing models can be also classified according to their objective functions: (1) minimizing energy consumption over a single routing session;[3, 13, 24] (2) maximizing network life,[23, 27] which is defined as the lifetime of the first node that runs out of battery power; (3) maximizing the predefined utility function,[25] which can be related to cost, link quality, and delay.

Constraint-free routing models can also be classified according to the type of application: (1) unicast[3, 4, 13, 20, 24, 25, 27] routing between a source-destination pair; (2) multicast[5] routing between a source and a set of receivers; (3) data gathering (reverse multicast)[12] routing between a set of sources and a sink.

1.3. Reliability-Constraint Link Quality Models

1.3.1. *Minimizing energy consumption*

Banerjee and Misra[3] argue that minimum-energy routing should not be based solely on the energy spent in a single transmission, which is usually adopted in networks using reliable links. Instead, the total energy (including energy consumed by any necessary retransmission) is the proper metric to evaluate routing optimality. Therefore, the authors model link cost as a function of energy consumption for a single transmission attempt across the link and the link error rate. Figure 1.2 gives an

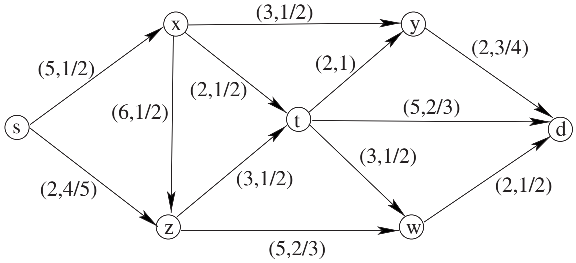

Fig. 1.2. An illustrative example where each link (i, j) is labeled with a two tuple $(e_{i,j}, q_{i,j})$ and each node is labeled with its ID.

example network graph where each link is labeled with two attributes (the energy consumption for a single transmission and the link error rate) in the form (energy, error rate).

The authors[3] consider two retransmission models: hop-by-hop and end-to-end. In the end-to-end retransmission model, data delivery is guaranteed through the retransmissions initiated by the routing source. In the hop-by-hop retransmission model, intermediate nodes provide link layer retransmissions to ensure reliable forwarding to subsequent hops.

For easy presentation, we use $e_{i,j}$ to denote the energy consumption of a single transmission across link (i, j), and $q_{i,j}$ to represent the link error rate. In the hop-by-hop retransmission model, the link cost $c_{i,j}$ is defined as

$$c_{i,j} = \frac{e_{i,j}}{1 - q_{i,j}}, \tag{1.1}$$

which is equivalent to the expected transmission count (ETX)[9] if $e_{i,j} = 1$. The ETX reflects the expected number of transmissions over link (i, j) under the condition that the number of retransmission is unlimited. Therefore, the definition of the link cost metric represents the expected energy consumption spent on a link. This link cost metric is additive for a path. Hence, the total energy cost of a path is the sum of the cost of each link on the path. The minimum cost path can be calculated through Dijkstra's algorithm. We use the example shown in Figure 1.2 to illustrate the minimum cost path in the hop-by-hop retransmission model. Figure 1.3 shows the cost of each link and the minimum cost from source s to each node of Figure 1.2. There are two minimum cost paths: $s \to x \to y \to d$ and $s \to x \to t \to w \to d$.

The authors[3] also consider total energy consumption along a path in the end-to-end retransmission model. To derive a closed form expression of the total path energy cost in the absence of hop-by-hop retransmissions, the authors make a simplified assumption that transmission errors on a link do not prohibit downstream nodes from relaying the packet. Therefore, the total energy consumption along path

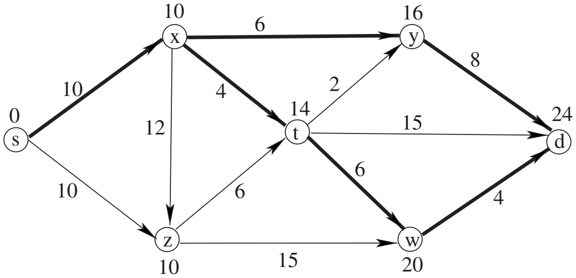

Fig. 1.3. This example illustrates the minimum cost path in the hop-by-hop retransmission model that provides link layer reliability. The topology of this example is the same as the example in Figure 1.2. The link cost $c_{i,j}$, which is labeled with each link (i,j), is calculated according to (1.1) based on transmission energy $e_{i,j}$ and link error rate $q_{i,j}$ provided in Figure 1.2. The number labeled with each node is the minimum cost from source s to the node. The bolded paths represent the minimum cost paths.

P is defined as:

$$C_P = \frac{\sum_{(i,j)\in P} e_{i,j}}{\prod_{(i,j)\in P}(1-q_{i,j})}. \tag{1.2}$$

The above formulation cannot be expressed as a line sum of individual link costs, thereby making it inappropriate for the existing minimum-cost path computation algorithms. The authors[3] approximate Equation (1.2) by identifying all links on a path, i.e. assuming each link has the same transmission energy cost and link error rate. Therefore, Eq (1.2) can be reduced to

$$C_P = \frac{ke}{(1-q)^k}, \tag{1.3}$$

where k is the number of links on path P, e is the transmission energy cost, and q is the link error rate. Based on Equation (1.3), the authors[3] propose a heuristic cost function for a link as follows:

$$c_{i,j}^{approx} = \frac{e_{i,j}}{(1-q_{i,j})^L}, \tag{1.4}$$

where $L = 2, 3, \ldots$, and is chosen to be identical for all links. Hence, the total energy consumption of a path is approximated as the sum of $c_{i,j}^{approx}$ for each link on the path. In Figure 1.4, we illustrate the minimum cost path in the simplified end-to-end retransmission model. The minimum cost path when $L = 2$ for this example is $s \to x \to t \to w \to d$, which is different from that of Figure 1.3.

By analyzing the interplay between error rates, number of hops, and transmission power levels, the authors[3] concluded the following: (1) a path with multiple shorter hops is not always more beneficial than one with a smaller number of long-distance hops; (2) a routing algorithm should evaluate a candidate link (and the path) on the

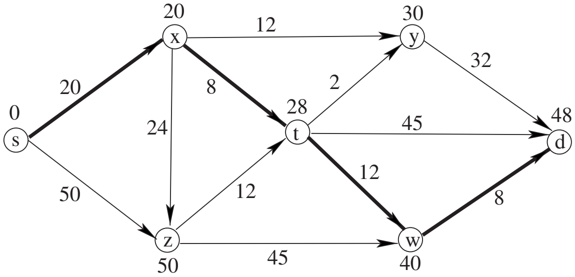

Fig. 1.4. This example illustrates the minimum cost path in the simplified end-to-end retransmission model that provides end-to-end reliability. The topology of this example is the same as the example in Figure 1.2. The link cost $c_{i,j}$, which is labeled with each link (i, j), is calculated according to (1.4) based on the transmission energy $e_{i,j}$ and link error rate $q_{i,j}$ provided in Figure 1.2. The number labeled with each node is the minimum cost from source s to the node. The bolded path represents the minimum cost path.

basis of both its power requirement and its error rate; (3) link-layer retransmission support is almost mandatory for a wireless ad hoc network because it can reduce the total energy consumption by at least one order of magnitude; (4) the advantage of using the retransmission-aware scheme is significant regardless of whether fixed or variable transmission power is used; (5) traditional Dijkstra- and Bellman-Ford-based routing algorithms can be adapted to compute the optimal energy-efficient route for the case where link layers implement perfect reliability.

Banerjee *et al.*[13] extend this work[3] by relaxing the assumption of perfect reliability in the link layer. The authors explain that all practical mechanisms achieve perfect end-to-end reliability through either end-to-end retransmission or the mixed approach (combination of hop-by-hop retransmission and end-to-end retransmission). To address the problems one at a time, they first consider the pure end-to-end retransmission model, then the mixed retransmission model.

When designing routing algorithms, the first challenge lies in defining the link cost function. In the hop-by-hop retransmission model,[3] the accumulated energy cost for a link is easy to express because it depends only on the energy spent on a single transmission across the link and the corresponding link error rate. In the pure end-to-end retransmission model, the accumulated energy consumption depends not only on the local link error rate but also on the link error rates of its downstream links. Although the authors[13] propose an expression for the link cost function in the pure end-to-end model, it is only an approximation. Banerjee *et al.*[13] improve their work by introducing a recursive expression for the accumulated energy consumption in the pure end-to-end retransmission model, which can calculate the exact energy cost of a path rather than just approximating it.

Assume that node u precedes v in the path from s to v, denoted by $P_{s,v}$. Let $P_{s,u}$ denote the pair of $P_{s,v}$ between s and u. For any path $P_{i,j}$, let $C_{P_{i,j}}$ denote the energy consumed when a packet is successfully delivered along the path from i to j. The recursive expression for the accumulated energy consumption is

$$C_{P_{s,v}} = ETX_{u,v} \cdot (C_{P_{s,u}} + e_{u,v}), \tag{1.5}$$

where $ETX_{u,v}$ is the ETX of link (u, v), and $e_{u,v}$ is the energy consumption of a single transmission attempt across link (u, v). In Dijkstra's algorithm[8] where all links are assumed to be reliable, the energy cost of a path can also be expressed in a recursive form: $C_{P_{s,v}} = C_{P_{s,u}} + e_{u,v}$. Comparing this recursive expression with Equation (1.5), it is easy to see that Dijkstra's algorithm can be used to compute the minimum accumulated energy path in pure end-to-end retransmission models by replacing the pseudo-code $C_{P_{s,v}} = \min\{C_{P_{s,v}}, C_{P_{s,u}} + e_{u,v}\}$ with the pseudo-code $C_{P_{s,v}} = \min\{C_{P_{s,v}}, ETX_{u,v} \cdot (C_{P_{s,u}} + e_{u,v})\}$.

The computation of the minimum accumulated energy path can be illustrated through the example in Figure 1.5. In the example network, each link (i, j) is labeled with a two tuple $(e_{i,j}, ETX_{i,j})$, and each node is labeled with its ID. x is the first node added except the source s, followed by its successors z and t, respectively. This process terminates after choosing d, whose predecessor is t. The minimum accumulated energy path is $s \to x \to t \to d$ with accumulated energy 87. Without considering link loss rates, a naïve shortest path is $s \to z \to w \to d$.

The authors[13] also extend the result of the pure end-to-end retransmission model to the more general mixed retransmission model where some of the links support hop-by-hop retransmissions and end-to-end retransmission is guaranteed. In Ref. 13, the authors derive a recursive expression for the accumulated energy consumption in the mixed retransmission model as follows:

$$C_{P_{s,v}} = \begin{cases} C_{P_{s,u}} + ETX_{u,v} \cdot e_{u,v}, & \text{if hop-by-hop} \\ ETX_{u,v} \cdot (C_{P_{s,u}} + e_{u,v}), & \text{otherwise} \end{cases},$$

which is based on Equations (1.1) and (1.5). In the above expression, "if hop-by-hop" means that link layer retransmission is provided to support link layer reliability.

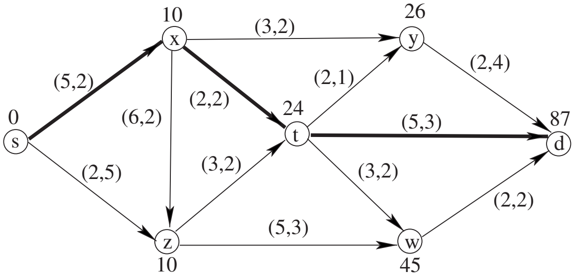

Fig. 1.5. This example illustrates the minimum cost path in the pure end-to-end retransmission model that provides end-to-end reliability. The topology of this example is the same as the example in Figure 1.2. Each link (i, j) is labeled with a two tuple $(e_{i,j}, ETX_{i,j})$. The number labeled with each node is the minimum cost from source s to the node. The bolded path represents the minimum cost path.

The minimum cost path in the mixed retransmission model can be computed by the modified Dijkstra's algorithm, which replaces the pseudo-code $C_{P_{s,v}} = \min\{C_{P_{s,v}}, C_{P_{s,u}} + e_{u,v}\}$ from the original Dijkstra's algorithm with the following pseudo-codes: $C_{P_{s,v}} = \min\{C_{P_{s,v}}, C_{P_{s,u}} + ETX_{u,v} \cdot e_{u,v}\}$ if link layer reliability is supported by link layer retransmissions; otherwise, $C_{P_{s,v}} = \min\{C_{P_{s,v}}, ETX_{u,v} \cdot (C_{P_{s,u}} + e_{u,v})\}$. In Figure 1.5, if we assume link (y, d) is reliable due to link layer retransmissions, the minimum cost path changes to $s \rightarrow x \rightarrow y \rightarrow d$ with minimum cost 34.

Based on centralized algorithms, the authors propose a non-trivial, lightweight (in terms of route exchange information), distributed algorithm. The authors also consider a multi-path routing scheme for the mixed retransmission model. The authors prove that the multi-path routing problem is NP-hard by reducing from the 3-dimensional matching problem.

Li and Shu *et al.*[24] extend previous works by integrating power control techniques into the routing problem proposed in Ref. 13. In Ref. 3, the authors model link error rates as functions of the received signal strength. In the variable-power scenario, the authors fix the received signal strength to the minimum signal strength to minimize the transmission energy across a link so that the transmitted data can be successfully decoded from the received signal. However, due to the existence of link error, the predetermination of the received signal strength, which in turn determines the transmission power, does not necessarily minimize the effective energy consumption on that link. Therefore, Li and Shu *et al.* adopt power control methods to minimize the effective energy consumption and integrate computation of the optimal transmission power into the routing algorithms[3, 13] for the reliable hop-by-hop model, the reliable end-to-end model, and the mixed model. The authors[24] also extend the unicast routing problem to single sink multiple unicast routing, multi-path (disjoint path) routing, and overlay based multi-cast routing, as well. For the first two routing problems, the authors[24] propose optimal algorithms, while for multi-path routing, the authors propose an approximation algorithm with approximation ratio 2.

Li and Shu *et al.*[24] also consider the case of bounded retransmission times in the link layer. However, they have a technical flaw in their definitions of the link cost and link error rate. Due to bounded retransmission times, the link cost is not simply the multiplication of the transmission cost across the link and the maximum allowed transmission attempts. The reason is that each transmission attempt occurs with a different probability and no retransmission is needed after a successful transmission attempt.

The bounded retransmission scheme is a generalization of the unbounded retransmission scheme because the latter can be regarded as the maximum number of transmissions, being infinity. Therefore, it is more general to study the above routing problems in case of the bounded retransmission times.

Cristescu and Beferull-Lozano[11] consider a sensor network that measures correlated data, where the task is to gather all data from the network nodes to a sink.

They consider the case where data at nodes is lossy coded with high-resolution, and the information measured by the nodes should be available at the sink within certain total and individual distortion bounds. First, they consider the problem of finding the optimal transmission structure and the rate-distortion allocations at various spatially located nodes, so as to minimize the total power consumption cost of the network. They prove that the optimal transmission structure is the shortest path tree and that the problems of rate and distortion allocation separate in the high-resolution case; namely, they first find the distortion allocation as a function of the transmission structure, and then the rate allocation is computed. Then, they study the case when the node positions can be chosen by finding the optimal node placement when two different targets of interest are considered, namely total power minimization and network lifetime extension.

1.3.2. *Maximization of network lifetime*

Kwon *et al.*[23] propose a network lifetime maximization problem under reliability and stability constraints in wireless sensor networks. The authors assume that wireless links are unreliable due to channel error alone, and modeled the link stability (per-hop probability of successful packet delivery) as a function of channel gain and transmission power. To address these problems one at a time, the authors first propose a retry limit allocation problem, similar to our quota assignment problem.[25] For a given path from a sensor to a sink, assuming the transmission power for each sensor is fixed and equivalent, the retry limit allocation problem focuses on allocating the number of transmissions to each sensor along the path. The objective of this problem is to minimize the total expected energy consumption of this path. The constraint is that the packet delivery probability along this path should be no less than a threshold probability. Kwon *et al.*[23] propose a greedy solution to this problem. This greedy solution first assigns each link one retry limit and then iteratively selects a link to increase its retry limit. The retry limit of a selected link is always increased one at a time. Each time, the selected link must be the one that can increase its link reliability the most. This process repeats until the reliability constraint is satisfied.

The authors[23] then propose a routing and power control problem. They assume that multiple paths between a particular sensor and sink pair exist. The objective of this problem is to balance the energy consumption among all possible paths from each sensor to the sink so that the network lifetime can be maximized. Besides selecting the amount of data transmitted along each path, the authors also consider the selection transmission power level and determine the retry limit on each link. Two solutions are provided to solve the problem. One is a linear programming based solution, which is optimal. The other is a cost-based heuristic solution.

The Maximum Residual Packet Capacity (MRPC) protocol proposed in Ref. 27, which considers battery charge as well as link reliability during route selection.

In Ref. 27, a node-link metric is introduced to capture the energy-lifetime of a link between nodes i (transmitter) and j, which is defined as:

$$L_{i,j} = \frac{R_i}{E_{i,j}},$$

where R_i is the residual battery charge at node i and $E_{i,j}$ is the energy required to transmit a data packet of given size over link (i, j). A suggested formulation for $E_{i,j}$ is as follows:

$$E_{i,j} = \frac{T_{i,j}}{(1 - p_{i,j})^H},$$

where $T_{i,j}$ is the energy required for one transmission attempt of the aforementioned data packet with a fixed transmission power. Also, $p_{i,j}$ is the packet error probability of the link (i, j) and $H = 1$ if unlimited hop-by-hop retransmissions are performed by the link layer. From the above formulae, it is clear that the lifetime of a link is higher when greater battery charge remains at the transmitter node, and when the reliability of the link is high, resulting in a low energy cost for correctly transmitting a packet. These formulae give an estimation for the expected number of data packets that can be transmitted over a link before the battery of the transmitter fails. If a route failure is said to occur when any single link on it fails, the lifetime of path p in number of packets is simply:

$$Life_p = \min_{(i,j)\in p} \{L_{i,j}\}.$$

MRPC considers the best route to be the one with the greatest residual lifetime. The authors suggest that the MRPC algorithm may be implemented in AODV[28] for application in MANETs. As routes are discovered, the lifetime of the path is accumulated by calculating the lifetime of each link. The next hop to a destination is always selected to be the neighbor which results in the greatest possible value for $Life_p$.

This protocol[27] results not only in load balancing, increasing the life of the network, and avoiding congestion, but also yields closer-to-optimal energy consumption per packet, as well as lower packet delay and packet loss probability due to the preference for more reliable links. It can also be implemented in an on-demand, fully distributed routing protocol, such as AODV. However, the estimation of the link reliability is not addressed.

1.4. Maximizing Reliability

1.4.1. *Opportunistic routing*

Opportunistic routing[4] utilizes redundancy in omnidirectional transmissions to make up for packet loss over lossy links. Intuitively, the wireless channels between a pair of nodes change over time, but if there are multiple receivers for a sender, then the probability of successful delivery is likely to increase.

The opportunistic routing scheme consists of two components: a routing component and a MAC component. The routing component is used to select candidate receivers for each node and determine their priorities, while the MAC component is responsible for identifying one receiver from the candidate receivers based on their priority and actual reception of packets. However, the above cross-layer routing scheme has three shortcomings. First, it does not propose an explicit optimization goal. Second, its MAC component cannot guarantee that only one receiver forwards packets. Third, the transmission range is fixed, which is unreasonable for selecting candidate receivers.

We simplified the above cross-layer routing scheme into a single-layer opportunistic routing scheme, present an explicit optimization goal, design an efficient algorithm that allows adjustable transmission ranges, prove the optimality of our algorithm, and implement the algorithm in both centralized and distributed ways. To simplify our model, we consider only one source-destination pair. Our distributed implementation provides a framework to implement routing components for all on-demand and opportunistic-based routing protocols. In our distributed implementation, only the summarized routing information, the expected network utility, is propagated from the destination to the source. Our scheme is easy to implement based on existing reactive routing protocols without introducing additional cost.

1.4.2. *Code redundancy-based reliability models*

In many transport protocols, reliability is achieved using acknowledgments and retransmissions. An alternative approach is to use replication (redundancy) and send identical copies of a message simultaneously over multiple paths to mitigate the effects of a single path failure.[31] This is in contrast to retransmission schemes which typically wait for a message to be lost before sending another copy. At the same time, erasure coding techniques have long been used to cope with partial data loss efficiently.[5]

Erasure coding[16] is a coding technique that converts a message into a set of coded packets such that any sufficiently large subset of the coded packets can be used to reconstruct the original message. In this paper, we assume that the original message has been split into k equally-sized packets. From the angle of linear algebra, each packet split from the original message can be regarded as a variable, and an erasure-coded packet is a linear combination of the k original packets. This can be expressed as a linear equation where the left-hand side of the equation is the linear combination of the k original packets and the right-hand side is the erasure-coded packet. As long as k linearly independent coded packets are given, the original message can be reconstructed by solving k linearly independent equations associated with the k coded packets.

In Ref. 20, Jain *et al.* apply erasure coding to delay tolerant networks (DTNs). Through both derivations and simulations, the authors find that there is no simple "one size fits all" answer to the question of whether erasure coding is beneficial. They outline three different regimes based on the underlying path failure probabilities and redundancy used. Using ideas from modern portfolio theory,[1] the authors propose an efficient algorithm to solve the above problem and demonstrate its efficacy as compared to simple replication and other heuristics in three different DTN scenarios.

Cui *et al.*[12] propose a jointly opportunistic source coding and opportunistic routing (OSCOR) protocol for correlated data gathering in wireless sensor networks. OSCOR improves data gathering efficiency by exploiting opportunistic data compression and cooperative diversity associated with wireless broadcast advantage. OSCOR is a cross-layer protocol. At the MAC layer, sensor nodes need to coordinate wireless transmission and packet forwarding to exploit multi-user diversity in packet reception. At the network layer, in order to achieve high diversity and compression gains, routing must be based on a metric that is dependent not only on link quality, but also compression opportunities. At the application layer, sensor nodes need a distributed source coding algorithm that has low coordination overhead and does not require that the source distributions be known. OSCOR provides solutions incorporating a slightly modified 802.11 MAC, a distributed source coding scheme based on the Lempel-Ziv code and network coding, and a node compression ratio dependent metric combined with a modified Dijkstra's algorithm for path selection. The performance of OSCOR is evaluated through simulations.

1.5. Maximizing Utility

In Ref. 25, we consider the unicast routing problem in wireless ad hoc networks with unreliable links in the scenario of the bounded retransmission times at the link layer. We first introduce a formula to calculate the expected number of transmissions given the maximum number of allowed transmissions. The expected energy consumed on a link is therefore the link transmission cost times the expected number of transmissions. We find that it is meaningless to compute the path with minimum expected energy consumption, as previous works[3, 13, 24] did. We observe that the minimum-expected-energy path can be a path consisting of links with high error rates. In the extreme case, the energy cost of a path can be 0 if a node on the path which does not forward packets exists. In a pure hop-by-hop model, if the maximum number of transmissions is bounded, the delivery of packets cannot be guaranteed. If we only pursue the minimization of the effective energy consumption and ignore the fundamental objective, the delivery of packets to their destination, the optimal path is meaningless. In fact, a trade-off exists between the minimization of the effective energy consumption and the maximization of packet delivery ratio.

Therefore, we model a wireless ad hoc network as a market, introduce the concept of benefit, and adopt benefit to reflect the willingness of a source node to balance the maximization of packet delivery ratio and the minimization of effective energy consumption. The link cost is no longer only dependent on its own properties: the energy cost for a single transmission across the link and its link error rate. Therefore, the introduction of the bound of the transmission times incurs interdependence between a node's expected cost and its upstream nodes' link error rates.

1.6. The Measurement of Link Quality

In networks with abundant resources, such as the Internet, link quality is usually estimated by sending passive probing packets using the Internal Gateway Routing Protocol. Link quality is measured as the ratio of arrived packets to the expected packets. However, in such networks, each packet is transmitted along a particular link, which is known a priori. Packets in wireless networks, sent via a broadcast medium, can easily get lost due to different environmental and network factors. Thus, the pattern of link quality in wireless ad hoc/sensor networks is expected to be very different from the Internet. Wireless local area network (e.g. IEEE 802.11) and sensor networks share similar qualitative communication patterns.[2] The link qualities of wireless ad hoc and local area networks are studied in Refs. 10 and 26, which demonstrate that shortest path routing may not yield a satisfactory performance due to the variance of communication links. Due to the unique characteristics of sensor networks (e.g. high node deployment density and restrictions on energy), the measurement of link quality in wireless sensor networks is different from wireless ad hoc networks.

The research results on measuring wireless link quality and patterns in wireless sensor networks[6,7,15,39,41] have demonstrated that the communication range of a sensor node varies temporally and spatially. These variations have a major impact on data acquisition, packet delivery, and reliability of the network infrastructure; hence, they affect the network performance significantly. In order to incorporate the awareness of link quality in the design and operation of wireless ad hoc/sensor networks, research projects such as Refs. 32 and 33 have modeled the pattern of link quality changes over time. Woo *et al.*[32,33] observe that the link quality between a pair of sensor nodes has a statistical relationship to time. By tracking the packets heard/overheard, a sensor node is able to extract the trend of link quality changes over time and use it to estimate future link quality.

Woo *et al.*[32,33] define link quality as: packets received in t/max (packets expected to be received in t, packets received in t), where t is a time window. Thus, for an estimator to measure the link quality, a minimum rate for message exchange between neighbor sensor nodes is required. However, the number of messages generated for link quality estimation has a direct impact on the expected lifetime of the networks. For instance, a typical sensor network may last for about one month if each sensor node broadcasts a beacon message every 30 seconds; however, the network lifetime may be increased to more than ten months if each sensor node broadcasts a beacon

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every 10 minutes.[18] Moreover, frequent message exchanges may cause an upsurge in network traffic when node density is increased, which may further result in a number of problems in the network, such as transmission collisions, network congestion, lower transmission throughput, high packet transmission delay, and unreliability. This is a crucial issue since high node density widely exists in many sensor networks and applications. Xu and Li[34] develop a new link quality estimator that meets the goal of estimating the quality of links without degrading network performance.

Xu and Li[34] study the link quality of wireless sensor nodes by exploiting the spatial correlation in links. The intuition behind spatial correlation is that sensor nodes geographically close to each other may have correlated link quality. The spatial correlation in link quality is observed in Ref. 38, and has been further exploited by Xu and Li,[34] where the spatial correlation in link quality of neighbor sensor nodes can be captured to estimate the link quality with substantially less transmission cost than the link quality estimators based on temporal correlation. The historical information of link quality for one node may be used for estimating not only its own link quality but also that of other neighbor sensor nodes that are geographically close. Xu and Li[34] propose a weighted regression algorithm which allows each sensor node to capture the spatial correlation in the quality of its links. By categorizing the links into classes in accordance with their quality ranges and then employing a separate regression model for each class, the link quality at a given geographical point can be estimated to a high degree of accuracy.

Predictors or estimators are widely used in various systems and applications. Raghunathan *et al.*[29] point out that sensor networks exhibit significantly correlated variations in computing and communication workloads. Thus, the energy usage can be optimized by setting the voltage accordingly if the workload of individual tasks can be predicted. Goel *et al.*[17] and Xu *et al.*[35] predict the future movements of mobile objects to reduce the network communications for reporting sensor readings to a base station. Hu and Evans[19] propose a localization algorithm for mobile sensor networks, which predicts the location of mobile sensor nodes based on their previous locations and the maximum velocity.

1.7. Conclusion and Future Work

Due to the underlying wireless medium and the infrastructure-less nature, the communication between a pair of nodes is relatively unstable. Existing techniques compensate for the instability of wireless links by employing either packet retransmissions, network coding, opportunistic routing, thick (multiple) paths, or route fixes (using alternative routes). All these methods have their own advantages and disadvantages when it comes to increasing the reliability of wireless links. Hop-by-hop retransmissions have a great impact on increasing the reliability of low-quality wireless links with relatively low expected energy cost, but hop-by-hop retransmissions cannot increase the reliability much as the maximum number of retransmissions reaches a threshold value. Meanwhile, delay caused by retransmission is a problem for hop-by-hop retransmissions. On the other hand, network coding (especially erasure-based coding) can increase the reliability almost to 1 at the expense of more energy consumption than that of the hop-by-hop retransmissions. Delay incurred encoding and decoding is also a problem.

Opportunistic routing utilizes the wireless broadcast advantage property in order to increase the bandwidth of data transmissions, which in turn can increase the reliability of data transmissions. The drawbacks of opportunistic routing are as follows: (1) its application is limited to low traffic scenarios; (2) there is a long delay caused by the requirement that each subsequent hop has to send acknowledgements in a back-off fashion. Route fixes and multiple path methods can also increase reliability, but they increase route discovery costs and introduce routing management difficulties such as data allocation problems in multiple paths.

Two important metrics for evaluating the above techniques are reliability and cost. Many works consider the problem of minimizing the energy cost by assuming that the end-to-end reliability can be guaranteed by the unlimited hop-by-hop retransmissions; this is not true because the number of hop-by-hop retransmissions is bounded in practical link layer implementation. If the end-to-end transmission is not 100%, cost alone cannot reflect the whole story because, in the presence of loss, one may incur cost and not do useful work. To balance the trade-off between reliability and cost, we could introduce the utility of packets which reflect the importance of data. If data has high importance, it is preferable to select a technique with higher reliability even with higher cost. Otherwise, it is desirable to select a technique with lower cost.

To fully utilize the advantages of the above techniques and reduce the bad impact brought by the disadvantages, it is natural to consider the combination of the techniques mentioned above. Several previous works have considered the combination of retransmission, route fixing, and erasure coding in different network models. However, as network coding continues to develop and opportunistic routing is introduced, the capacity in which reliability could be improved increases dramatically. In future work, it is desirable to consider the combination of various techniques completely. Also, metrics other than merely reliability and cost, such as utility and delay, should be considered to further identify the best solutions in various applications.

Problems

(1) What is the difference between hop-by-hop retransmission and end-to-end retransmission?
(2) What is the difference between end-to-end coding and path coding?
(3) What is the difference between multiple paths and alternative paths?
(4) What is expected transmission count (ETX)? How does it relate to the expected cost in the hop-by-hop retransmission model?

(5) In Figure 1.5, the minimum cost path is $s \rightarrow x \rightarrow t \rightarrow d$. What are the ETXs of link (s, x), (x, t), and (t, d), respectively?

(6) In Figure 1.5, if we assume that link (y, d) is reliable due to the support of link layer reliability, the minimum cost path will be $s \rightarrow x \rightarrow y \rightarrow d$. What are the ETXs of link (s, x), (x, y), and (y, d), respectively?

(7) In opportunistic routing, why should candidate receivers be prioritized? What is the drawback of this prioritization?

(8) In utility-based routing, considering a direct-connected source and sink pair, what is the expected utility of a single transmission attempt in terms of link cost, link reliability, and packet benefit?

(9) What is Kwon *et al.*'s[23] to the network lifetime maximization problem?

(10) Please briefly describe how erasure coding can increase reliability and also discuss its drawbacks.

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