Routing with Uncertainty in Wireless Mesh Networks

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***Abstract*—Existing routing protocols for Wireless Mesh Networks (WMNs) are generally optimized with statistical link measures, while not addressing on the intrinsic uncertainty of wireless links. We show evidence that, with the transient link uncertainties at PHY and MAC layers, a pseudo-deterministic routing protocol that relies on average or historic statistics can hardly explore the full potentials of a multi-hop wireless mesh.**

We study optimal WMN routing using probing-based online anypath forwarding, with explicit consideration of transient link uncertainties. We show the underlying connection between WMN routing and the classic Canadian Traveller Problem (CTP) [1]. Inspired by a stochastic recoverable version of CTP (SRCTP), we develop a practical SRCTP-based online routing algorithm under link uncertainties. We study how dynamic next hop selection can be done with low cost, and derive a systematic selection order for minimizing transmission delay. We conduct simulation studies to verify the effectiveness of the SRCTP algorithms under diverse network configurations. In particular, compared to deterministic routing, reduction of end-to-end delay ($51.15\sim73.02\%$) and improvement on packet delivery ratio (99.76%) are observed.

I. Introduction

A Wireless Mesh Networks (WMNs) consists of backbone wireless routers that are relatively static and resource-rich, as well as wireless end-terminals that communicate through multi-hop routing, with possible Internet connection via the backbone routers. Given its cost-effectiveness in rapidly bringing a large number of users online, WMNs have enjoyed rapid growth in deployment during the past decade [2]. However, WMN routing has been notably challenging, despite much smaller network sizes than that of the Internet. Wireless links are intrinsically unreliable, at both long (session) and short (packet) time scales. The physical layer modulation switches dynamically, interference happens frequently, and effective link capacities fluctuate from time to time. All these are further complicated by the multi-hop relay of packets.

Given the uniqueness of WMNs, a series of routing protocols have been proposed, addressing link unreliability from various aspects [3]–[6]. While they are generally more reactive to link dynamics than Internet routing protocols, the elastics remain in a relatively long time scale. These routing algorithms strike to discover an optimal route and periodically update it, often in a relatively high frequency or per session demands. However, once determined, every relay node will have a fixed next hop for forwarding data. Better flexibility can be enabled by multi-path routing, but the next-hop selection for each individual packet is still largely based on pre-assignment or historic statistics [7], [8].

This convention however does not well-address the intrinsic uncertainty of wireless links, particularly in multi-hop routing. Intuitively, a link that statistically performs well on average may be unreliable and suffer from intermittent failures. A fixed route containing such a link consequently witnesses packet losses and long packet delays from time to time. During the intermittent failures, other links may be available with better performance. Such link availability and status information are discovered only in an *online* fashion, *i.e.*, at the time of transmission. In other words, with the transient link uncertainties at PHY and MAC layers, a (pseudo) deterministic routing protocol that relies on average or historic statistics can hardly explore the full potentials of a wireless mesh.

Recently, opportunistic routing (OR) was proposed [9], [10] to cope with the unreliability of wireless links. OR exploits the broadcast nature of wireless transmission, and runs a forwarder selection procedure to decide which node in the neighborhood of the transmitter further relays the packet. While leading to improved throughput, OR protocols are also known to incur control overhead due to the forwarder selection at each hop, contributing to prolonged end-to-end packet delays.

We propose to study delay-optimal routing in WMNs using a *probing based online* anypath forwarding approach, with explicit consideration of transient link uncertainties. We establish the underlying connection between WMN routing and a Stochastic Recoverable version of the classic Canadian Traveller Problem (SRCTP) [1], and develop an SRCTP-based online routing algorithm for delay minimization. As a key operation of this stochastic algorithm, a node performs online probing of its neighbors' availability upon each packet transmission, and determines its next hop on the fly accordingly. We study how such probes can be done with low cost, and derive a systematic probing scheme for delay minimization.

Through extensive simulations, we demonstrate the effectiveness of SRCTP under various network configurations. In particular, we observed considerable reduction on end-to-end delay ($51.15\sim73.02\%$) and improvement on packet delivery ratio (99.76%), as compared to traditional WMN routing.

The rest of the paper is organized as follows. Sec. II presents related research, and Sec. III describes the network model. Sec. IV presents the SRCTP online routing algorithm. We

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conduct simulations in Sec. V. And in Sec. VI, we conclude the paper.

II. Previsous Research

Wireless transmissions are susceptible to spatial interference, and routing in multi-hop wireless networks faces significant challenges even with relatively small network sizes. Recent studies exist in modeling WMN routing as a mathematical programming problem [11]–[13]. Classic sub-gradient search methods and convex duality theory are then applied [12]. Dynamic links have also been considered, and Lyapunov stability theory is used to solve the problem [13]. These solutions require knowledge of the global network topology and the traffic matrix. Our model instead targets distributed node operations, and focuses on the intrinsic uncertainty of the wireless links. Rather than collecting the traffic matrix in advance, we integrate realtime channel probing and historical statistical information to achieve delay-minimized routing, with online next-hop selection.

This work also differs form on-demand routing protocols such as DSR [3] and AODV [4]. These protocols are designed mostly to cope with node movement and longer time scale topology changes in wireless networks. Recent studies have also been conducted on examining different routing metrics in WMNs, including expected transmission count in ETX [6], expected transmission time as a function of loss and link bandwidth [14], and total medium access time [15]. Given the stationary nature of mesh routers, these protocols are generally rendered to a semi-deterministic routing protocol. Our protocol however retains dynamic neighbor selection for every packet transmission, so as to fully explore the potentials of multiple neighbors. This implicitly enables multi-paths, yet departs from previous multi-path designs that rely on pre-calculation for dedicated secondary routes [7], [8].

ExOR [9] pioneered research of opportunistic routing (OR) in wireless networks, and made a practical proposal of using a forwarding set to replace a single next-hop candidate. Contrasting the OR algorithms, we perform next-hop selection among the candidate set *before*, instead of *after*, the current node transmission. As a result, we avoid the distributed coordination phase required for achieving consensus on a single forwarder.

Our work is inspired in part by the recent advances in stochastic routing [1], [16]. Existing formulations of stochastic routing however are usually NP-hard and are not customized for wireless mesh networks. We for the first time demonstrate its application in WMNs routing.

III. Model and Motivation

In this section, we first describe the network and transmission model, and then present a simple example that motivates our study.

A. Wireless Mesh Network and Transmission Model

A WMN can be modeled as a directed graph $G(V, E)$, where V is the set of mesh routers and E is the set of possible wireless links. A unicast route is from a source $n_s \in V$ to a destination $n_d \in V$, connected through multiple relay routers.

A wireless link (n_i, n_j) is generally unreliable due to noise and interference, and is associated with a failure probability p_{n_i,n_j} for not able to start a transmission at a given time point. In this paper, we use a *two-state* model: at any specific time, each link is either *failed* with zero transmission rate, or *working* with full transmission rate r_{n_i,n_j} (with probability $q_{n_i,n_j} = 1 - p_{n_i,n_j}$).

In this binary link model, when a node n_i has a packet for a neighbor n_j, it needs to probe the link. Such a probe can be conducted through a number of techniques, *e.g.*, using the 802.11 RTS/CTS control messages [17], [18]. If the link is working, a transmission can be initialized; otherwise, node n_i waits for time $\Delta\mathbb{T}$, which includes the time to wait for neighboring transmissions that cause interference and the random back-off time in the 802.11 MAC. This link transmission process is illustrated in Fig. 1, where τ is the mean value of $\Delta\mathbb{T}$. The expected delay from n_i to n_j can be derived as

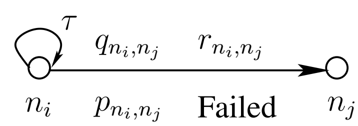


Fig. 1. Link and transmission model.

$$\mathrm{E}(t) = (qB/r + p\tau)/q \ , \tag{1}$$

where B is the packet size.

This generic model is widely adopted in the literature of wireless networks, for capturing the fundamental uncertainty of wireless transmissions. A number of routing protocols were designed using this model with diverse routing metrics [3]–[6]. Unfortunately, they are in general *deterministic* in the sense that these routing algorithms strike to discover and maintain a static route between periodical route updates. We next use an example to illustrate that this approach does not fully explore the potentials of WMNs.

B. A Motivating Example for Stochastic Routing

Fig. 2 depicts four nodes n_s, n_1, n_2, n_d, connected by four wireless links, with failure probabilities labelled.

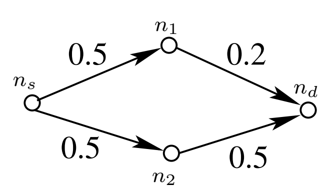


Fig. 2. An example WMN session from n_s to n_d, with link failure probability beside each link.

For a routing request from source n_s to destination n_d, traditional routing algorithms will choose n_1 as the relay, because on average link (n_1, n_d) is better than (n_2, n_d). Assume $B/r = 1$ and $\tau = 1$, we use Eq. (1) to calculate the expected delay from n_s to n_d of the two possible routes:

$$n_s \to n_1 \to n_d : \frac{0.5*1+0.5*1}{0.5} + \frac{0.8*1+0.2*1}{0.8} = 3.25$$
$$n_s \to n_2 \to n_d : \frac{0.5*1+0.5*1}{0.5} + \frac{0.5*1+0.5*1}{0.5} = 4$$

Therefore the choice of traditional deterministic routing seems rational. Unfortunately, this lower delay of 3.25 is actually far from the optimal, at 2.83. We will give rigorous derivation of the optimal delay later in Section IV. For now, an intuitive explanation is that, although on average better than (n_2, n_d), link (n_1, n_d) remains unreliable and fails for 20% of the time. If we stick to this link, we will suffer from such failures from time to time, even the other link (n_2, n_d)) may be working in the mean time.

This observation motivates our design of stochastic *online* routing algorithms under link uncertainty. We suggest that each node dynamically determines its next hop through online link status probes; only when all the available links are failed will the node have to back off. Different than traditional multi-path routing, there is no pre-computed next-hop neighbor set. Different than opportunistic routing, a calculated next hop selection is performed *before*, not *after*, the real packet transmission.

IV. Stochastic Routing with Link Uncertainty

While the stochastic routing approach appears promising, there are a number of challenges in realizing it for WMNs. In this section, we first introduce the Stochastic Recoverable Canadian Traveler Problem (SRCTP) [16]. We show the underlying connections between SRCTP and WMN routing, identify and overcome the difficulties in mapping the latter to the former, and develop an online delay-optimal routing protocol under link uncertainty.

A. The Canadian Traveler Problem

The Canadian Traveler Problem (CTP), first introduced by Papadimitriou and Yannakakis in 1989, is an online optimization problem with incomplete information [1]. Consider a traveler in Canada who wants to drive from Vancouver to Toronto in winter. The traveler has a map with road directions and distances. However, given the severe weather conditions, some roads may be blocked by snowfalls, and such blockage would only be revealed when the traveler reaches an adjacent city. The problem is to devise a travel strategy with minimum expected travel time.

Devising a strategy that grantees a constant competitive ratio for CTP is PSPACE-Complete [16]. Approximate solutions have been applied in fields such as transportation, planning, robot navigation [19]. With wireless link failures, naturally, the WMN routing problem also resembles CTP. However, we do have extra information on link statistics, *e.g.*, failure probabilities, which are not available in original CTP. A CTP variant with link blockage probabilities, Stochastic Recoverable-CTP (SRCTP), was examined in [16]. Interestingly, the extra information can indeed lead to an optimal polynomial-time solution: at each node, the next hop selection can be based on a priority list of the neighbors; the list is calculated with a shortest-path-like algorithm, and the first non-blocked neighbor from the list will be chosen.

Our study of stochastic WMN routing is motivated by SRCTP, which admits an optimal online strategy for minimizing expected traveling time. Nonetheless, the mapping from WMN routing to SRCTP remains non-trivial. Neither CTP or SRCTP considers the cost to discover non-blocked roads, which plays an important role in our design. We next address this challenge through a judicious probing strategy.

B. SRCTP-based Routing

Our online SRCTP-based routing protocol relies on a simple local operation, as illustrated in Fig. 3. Here, node n_i has k neighbor nodes $\{n_i^1, \ldots, n_i^k\}$, among which h neighbors are chosen as a *candidate set* for the next hop. Different from conventional routing protocols, we do not fix a neighbor as next hop based on average or historical measures, but dynamically select one through a probing process.

Specifically, n_i will first probe link (n_i, n_i^1), and will use that link if it works. If it fails, the next neighbor link (n_i, n_i^2) will be probed, and so forth until a link works or all the candidates have been probed. In the latter, n_i will back off for a random time with mean value τ. This back off time should be comparable to a packet transmission time to avoid collision. In this case, it also mitigates the dependency of link failures. Note that although a broadcast probe alternative is possible, it requires both a distributed response coordination and modifications to the existing 802.11 protocol, and is therefore undesirable. After the back off, a *round* finishes and n_i restarts another round of probing, and continues until finding a working link to transmit the data.

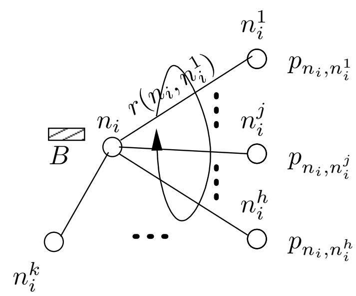


Fig. 3. Round robin probing of next hop candidates.

The delay performance of our protocol closely depends on the probing order of the neighbors. Like in conventional routing protocols, each node n_j keeps a list of the expected delay $\mathrm{E}(t(n_j, n_d))$ from itself to each destinations n_d, and such a list is exchanged between neighbors. Then, for node n_i, the expected delay of using a particular neighbor includes the link probing cost, the transmission time using this link, and the expected delay from the next hop node to the destination. For example, assume 802.11 RTS/CTS handshaking is used for channel probing. If the size of channel probing packets during handshaking is b, and the total inter-frame space included is T_{IFS}, then the cost for a channel probe can be calculated as:

$$T_{probe}(n_i, n_i^j) = 2b/r_{n_i,n_i^j} + T_{IFS} \qquad (2)$$

The expected delay for a working link can then be formulated as

$$I_j \triangleq T_{probe}(n_i, n_i^j) + B/r_{n_i,n_i^j} + \mathrm{E}(t(n_i^j, n_d)) \quad (3)$$

The smaller I is, the shorter delay can be expected. The neighbors should therefore be sorted in ascending order of their I values.

C. Size of Candidate Set

The size of the candidate set h also plays an important role in delay minimization. Intuitively, increasing h offers a better chance of finding a working link; yet it increases the probing cost, and a neighbor link with very high I value, even if working, would be of less interest for packet delivery. In that case, it is better to start another round of probing, and hopefully find a 'better' working neighbor.

To derive the optimal h, we insert adjacent links into the candidate set one-by-one, in ascending order of their I values. After each insertion, we update the expected delay to n_d using the temporary candidate set. The insertion continues until the expected delay increases. Let $\mathcal{C}_{n_i}$ be the candidate set so far. Similar to Eq. (1), we can obtain the expected delay as [1]

$$\mathrm{E}_1(t(n_i, n_d)) = (q_1 I_1 + p_1 \tau)/q_1 \quad (4)$$

For h neighbors in $\mathcal{C}_{n_i}$, let

$$P_h \triangleq \prod_{j=1}^{h} p_j, \qquad \alpha_h \triangleq \sum_{j=1}^{h} P_{j-1} q_j I_j \quad (5)$$

According to the probing process, the expected delay from n_i to n_d can be calculated as

$$\mathrm{E}_h(t(n_i, n_d)) = (\alpha_h + P_h \tau)/(1 - P_h) \quad (6)$$

The proof of the following theorem will be presented in the full version.

Theorem 1: The trend (increasing or decreasing) of $\mathrm{E}_h(t(n_i, n_d))$ to h solely depends on the sign of δ_h:

$$\delta_h \triangleq (1 - P_h) I_{h+1} - (\alpha_h + \tau) \quad (7)$$

Following the above theorem, if $\delta_h < 0$, the expected delay can be reduced by adding the $(h+1)$-th neighbor into the candidate set $\mathcal{C}_{n_i}$. If $\delta_h \geqslant 0$, there is no benefit of doing so.

Lemma 1: For $\forall h'$, if $\mathrm{E}_{h'+1}(n_i, n_d) \geqslant \mathrm{E}_{h'}(n_i, n_d)$, then $\forall h > h', \mathrm{E}_{h+1}(n_i, n_d) \geqslant \mathrm{E}_h(n_i, n_d)$.

Proof: Since $\mathrm{E}_{h'+1}(n_i, n_d) \geqslant \mathrm{E}_{h'}(n_i, n_d)$, we have $\delta_{h'} \geqslant 0$ according to Theorem 1.

Since the neighbor links are sorted in ascending order of I in Eq. (3), we have $I_{h'+2} \geqslant I_{h'+1}$. It follows that $\delta_{h'+1} \geqslant 0$. According to Theorem 1, the lemma is true. ■

For the optimal size of candidate set, we try to find the smallest h' (denoted as h^*) that satisfies $\mathrm{E}_{h^*+1}(n_i, n_d) \geqslant \mathrm{E}_{h^*}(n_i, n_d)$. If such h^* exists, it will be set to the optimal size of the candidate set. If there does not exist such h^*, *i.e.*, $\mathrm{E}_k(n_i, n_d) < \mathrm{E}_{k-1}(n_i, n_d)$, the candidate set will include all the k neighbors.

Lemma 1 also confirms the rationality of the aforementioned neighbor probing order. From the proof, we can see that h^* can simply be calculated through checking the sign of δ_h in Eq. (7). We add more neighbor nodes into $\mathcal{C}_{n_i}$, until $\delta_h \geqslant 0$ or $h = k$. Altogether, we have the following theorem.

Theorem 2: SRCTP routing algorithm minimizes the expected delivering delay under the two-state link model.

The rest of the proof to the theorem, besides Lemma 1, is similar to that of the stochastic Recoverable-CTP algorithm, and is omitted here due to space limitation.

V. Performance Evaluation

We now present simulation studies of the proposed SRCTP routing algorithms, and compare them to wireless routing algorithms with fixed neighbor selection. We have implemented SRCTP and traditional semi-deterministic routing using a dedicated simulator written in C++, with ns-2 generated traffic trace and network topologies. We use the dei9011 mr library [20], [21] that accompanies the ns-2 allinone package for producing multi-rate MAC-layer links, based on SNR rate adaption. A revised version of dei9011 mr is utilized for simulating two-state links by depressing transmission rates that are lower than maximum, *i.e.*, 11Mbps for 802.11b and 54Mbps for 802.11g.

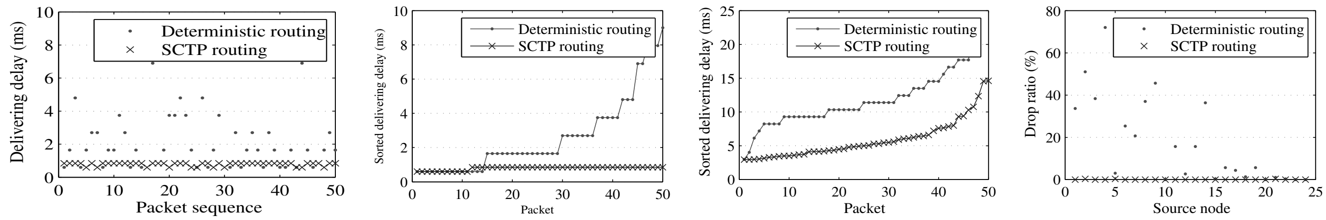
We evaluate SRCTP on both grid and random WMN topologies. The first is a 5×5 grid network with neighbor distance of 100m, same as in previous studies [22]. Transmission power is adjusted so that node transmission range is close to 150m. For random topologys, we used the Setdest tool from the ns-2 allinone package. We deploy 100 nodes in a $1200m \times 1200m$ area [23].

We compare SRCTP with traditional routing such as ETX [6], DSR [3] and AODV [4] in Fig. 4. For the latter, we select the first node in the candidate set built by our algorithms, and compare the performance against SRCTP in terms of end-to-end routing delay and packet delivery ratio.

Fig. 4(a) shows end-to-end delay of SRCTP and of deterministic routing, in the grid network topology, with 300 packets routed from the bottom-left node to the top-right node. Only 50 packets are shown, for figure clarity; the trend for 300 packets is similar. Fig. 4(b) depicts the same delays in ascending order. First, we observe that SRCTP outperforms deterministic routing in most except a few cases, by providing lower delays. Second, packet delays using SRCTP is much more stable than those using deterministic routing. SRCTP still demonstrates relatively better stability in the random network topology as showed in Fig. 4(c), with a highest delay of 15 ms, smaller than 20+ ms of deterministic routing. Furthermore, as in the grid topology, SRCTP leads to smaller end-to-end delay for most of the packets measured.

We conducted further simulations for measuring and comparing the packet loss ratio. Each packet is attempted for a maximum of 10 times for transmission at a given node, and dropped after that. Fig. 4(d) depicts drop ratios of both SRCTP

[1] Since here we focus only on node n_i, we use q_j to represent q_{n_i,n_i^j} and p_i to represent p_{n_i,n_i^j} for ease of exposition.



(a) End-to-end delay in grid network.

(b) Sorted delays in grid network.

(c) Sorted packet delays in the random topology.

(d) Packet drop ratios in the grid network.

Fig. 4. Performance comparisons, SRCTP *vs.* deterministic routing.

and deterministic routing. Unicast sessions, each containing 300 packets, are initialed from all other 24 nodes to the destination. Here the advantage of SRCTP is rather evident. A well-designed deterministic routing algorithm, such as DSR or AODV, would re-establish a new route upon a link failure, and the loss rate in practice will hence be more moderate than observed here. Nonetheless, we believe that SRCTP should still be superior since making online routing decisions at the link level is more flexible and effective than constantly re-computing the entire routing path.

VI. Conclusions

Wireless links are inherently stochastic and uncertain in that their quality and effective transmission rates are volatile, varying at both long and short time scales. This work proposes to optimize end-to-end packet routing delay with explicit consideration of such uncertainty in link qualities. We depart from the prefixed deterministic route selection, and apply online, stochastic route optimization instead. We model minimum delay routing as a stochastic optimization problem, and draw inspiration from the classic Canadian Traveler Problem, to design routing solutions for two-state links. Analysis and simulation results both show that considerable improvement over traditionally deterministic packet routing, in both end-to-end delay and packet delivery ratio, suggesting that the new probing-based online routing philosophy is indeed better suited for the nature of WMNs.

In the future, we will show more simulation results compared with opportunistic routings. Our solution selects the best forwarder in a centralized probing-based manner, preliminary simulation shows that it is normally better than the distributed coordinated forwarder selection mechanism in OR. Further, we will extend our two-state link model to multi-rate link model. It will follow the same probing-based online framework but with Stopping Theory as the theoretical tool. It shows that the probing-based philosophy is of online fashion, and rate adapter module can be easily decoupled with the routing algorithm to exploit real available transmission rate.

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