49th IEEE Conference on Decision and Control
December 15-17, 2010
Hilton Atlanta Hotel, Atlanta, GA, USA

Distributed Topology Control for Stable Path Routing in Multi-hop Wireless Networks

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Abstract— **In this paper, we introduce the stable path topology control problem for link-state routing in mobile multi-hop networks. We formulate the topology control problem of selective link-state broadcast as a graph pruning problem with restricted local neighborhood information. We develop a multi-agent optimization framework where the decision policies of each agent are restricted to local policies on incident edges and independent of the policies of other agents. We show that under a condition called the positivity condition, these independent local policies preserve the stable routing paths globally. We then provide an efficient algorithm, which we call the *Stable Path Topology Control* algorithm, to compute this local policy that yields a pruned graph. Using simulations, we demonstrate that this algorithm, when used with the popular ETX metric, outperforms topology control mechanisms commonly used for Mobile Ad Hoc Networks.**

I. Introduction

Topology control in wireless multi-hop networks has been a topic of active research in the recent years. Different topology control mechanisms have been proposed for various purposes, including connectivity, energy-efficiency, throughput and robustness to mobility [1]. In particular, several topology control algorithms, both centralized and distributed, that are aimed to reduce the *broadcast storm problem* have been developed [2]: *Broadcasting* in a network is the process by which a packet sent from one station reaches all other stations in the network. Several routing protocols in Mobile Ad Hoc Networks (MANETs) are proactive link state protocols, which broadcast the link state information. However, in these networks, the link states are highly dynamic, and consequently, a large number of packets, corresponding to every link state change, is broadcast in the network. This problem is referred to as the *broadcast storm problem* [2].

We adopt a graph pruning approach to reduce the broadcast storm problem for link state routing: by selecting a subset of the graph topology to be broadcast, the broadcast storm can be reduced [2]. Several of the pruning mechanisms proposed in literature are distributed localized algorithms [3], [4], [2], [5]. These local pruning algorithms have access to only their local neighborhood information (typically two-hop neighborhood information), which they prune to reduce the broadcast storm. Although there are a number of metrics that capture the link dynamics (Subsection II-A), few algorithms use these link metrics for topology control in routing. Even those that do are only heuristic methods; they do not offer proof guarantees for stability of the routing paths [6].

One important metric for routing in wireless multi-hop networks is path stability [7]. Although path stability has been studied for many reactive distance vector schemes [7], [8], there is little work that addresses topology control for stable paths in link state routing. We introduce a new topology control algorithm that guarantees stable path routing: a mechanism that prunes the initial topology (to reduce the broadcast storm) while guaranteeing that the stable paths (for unicast routing) from every host to any target station are preserved in the pruned topology. Topology control for stable paths has a two-fold advantage: First, these long lived paths are *cheaper to maintain* because they are less likely to change. Second, it offers the higher layer traffic long lived sessions and consequently yields *improved traffic carrying performance*.

The main contributions of this paper are the following. We formulate the *stable path topology control* problem as a *constrained multi-agent optimization problem*, where the agents include all the stations in the network, which have access to only their local neighborhood information. We formulate the pruning problem as a policy selection on the incident edges for each of these agents. Then we propose a policy for pruning and prove that this policy under a *positivity* condition guarantees that the stable routing paths are preserved. Finally, we develop a distributed pruning algorithm, which we call the *Stable Path Topology Control* (SPTC) algorithm, that solves the multi-agent optimization problem for our policy.

Our goal, in this paper, is not to engineer new link stability metrics, but to develop a general framework for the stable path topology control that can make use of any available link stability metric. We choose the ETX metric, a popular link stability metric, and apply it to the SPTC algorithm to demonstrate its performance. We call this the SPTC-ETX algorithm. This algorithm can be implemented with minor modifications to OLSR's neighbor discovery [9] and topology selection mechanism [10].

This paper is organized as follows. In Section II, we summarize related prior work. We also illustrate a fundamental limitation of the existing topology control algorithms. In Section III, we introduce the mathematical notations that is needed to formulate the stable path topology con-

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This material is based upon work supported by the Communications and Networks Consortium sponsored by the U.S. Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD19-01-2-0011 and the MURI Award Agreement W911-NF-0710287 from the Army Research Office.

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trol problem. In Section IV, we develop the mathematical framework for the multi-agent pruning problem. Finally in Section V, we present the SPTC pruning algorithm and using simulations, we demonstrate the performance of this SPTC-ETX algorithm.

II. Related Work

A more detailed summary of the related work is in our technical report [11].

A. Stability Metrics for Multi-Hop Wireless Networks

The wireless mesh networking community has been actively developing several stability metrics for routing [12]. To our knowledge, the earliest metric proposed, in this area, is the Expected Transmission Count (ETX) metric in [13], [14]. The ETX link metric computes the expected number of transmissions, including retransmissions, for a packet to reach a neighboring station. The authors of [13] design the ETX metric for 802.11 MAC with acknowledgements, and consequently, this ETX metric accounts for the link stability both in the forward and reverse direction of the link. This makes the link ETX metric symmetric. The ETX of a path is the sum of the link ETX metrics along the path. Although, currently it is not in the RFC [4], the ETX metric has been used in popular OLSR implementations [15], [16]. In this paper, we choose the ETX metric as an example link stability metric to compare the performance of our topology control algorithm (SPTC) with that of OLSR. There have been several other link stability metrics in the context of MANETs. See [11], for a detailed summary.

B. Limitations of Existing Topology Control Mechanisms

The algorithms that make use of the link stability metrics, in most cases, are modifications of reactive distance vector protocols. There are few proactive routing protocol that incorporate these link stability metrics for topology control for reduced flooding. Most of these are variants of OLSR's [4] pruning methods. For a brief summary of OLSR's pruning mechanism, see [11]. In [17], [6], [18], [16], the authors modify OLSR's MPR selection algorithm using a weighted set-cover algorithm [19]. In [15], [16], the ETX metric is used for link-stability weights. Let $ETX(u,v)$ be the symmetric ETX metric for the link (u,v). In the topology control algorithm proposed in [16], the host h computes the ETX metric of the best two-hop path to reach a two-hop neighbor j by $\min_l \textit{ETX}(h,i_l) + \textit{ETX}(i_l,j)$, where i_l's are the one-hop neighbors. The host then selects a minimal set of its one-hop neighbors (MPRs) that are in these best paths for each two-hop neighbor j. In essence, this is another set-cover problem [11], where all the two-hop neighbors are covered by a subset of one-hop neighbors using the computed ETX weights.

However, these set-cover methods offer no proof guarantees for the stability of the pruned paths, i.e., the stable paths for routing need not be preserved by these pruning methods. To illustrate this, consider an example weighted graph shown in Figure 1. The symmetric ETX metrics for

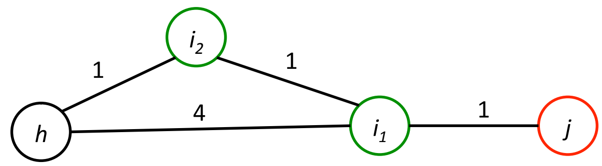

Fig. 1: Example Local View with ETX metric for each link indicated

the links are indicated in the figure. The host h has two one-hop neighbors i_1 and i_2 and one two-hop neighbor j. In this example, the link (h,i_1) is unstable (*ETX* $=4$), while all other links are stable. For this topology, the set cover method of the implementations in [16], [15] has only one feasible (two-hop) path (h,i_1,j) to reach j, which has an ETX cost 5. However, if we relax the artificial constraint of two-hop feasible paths, there exists an alternative better path (h,i_2,i_1,j) of ETX cost 3. Clearly, the set-cover pruning methods (of OLSR and its variants) will not preserve this stable path.

In the forthcoming sections, we will formulate and solve a distributed pruning problem that can provably preserve all the stable paths between every source-destination pair in the pruned topology. Our pruning method is not specific to any particular stability metric and can be applied for all the stability metrics summarized in [11].

III. Mathematical Notations and Definitions

A. Graphs and Neighborhoods

Let $G(V,E)$ denote the communication graph, where V is the vertex set and E is the undirected edge set. For $(u,v) \in E$, there is an associated symmetric link stability metric $a(u,v) = a(v,u) \geq 0$. Thus, G is an undirected edge-weighted graph. A subgraph of G, denoted by $G' \subseteq G$, is a graph $G'(V',E')$ such that $V' \subseteq V$ and $E' \subseteq E$ (restricted to $V' \times V'$). For any vertex $i \in V'$, the set of edges incident to i in any subgraph G' is denoted by $\Omega_{G'}(i)$. The set of paths in any subgraph G' between a pair of vertices $i,j \in G'$ is denoted by $P_{ij}^{G'}$. For any path $p \in P_{ij}^{G'}$, the *successor vertex* for a vertex i in p is denoted by η_p^i.

The hop count hc of a path is the number of edges in the path. Then the minimal hop count distance between a pair of vertices (i,j) in G is given by $d_{hc}(i,j) = \min_{p \in P_{ij}^G} hc(p)$. We define the *k-hop neighborhood* for a host $h \in V$ by $N_h^k = \{j \in V : d_{hc}(h,j) \leq k$. Here, k is called the *size of the neighborhood*. The boundary set for the neighborhood N_h^k is given by $\partial N_h^k = N_h^k \backslash N_h^{k-1}$, where $N_h^0 = \{h\}$, and $N_h^k = \emptyset, k < 0$. Let $N_h^{k^-} = N_h^k \backslash \{h\}$ denote the *exclusive* neighborhood, which is the neighborhood excluding h.

Consider a special induced subgraph G_h^{local}, which is a subgraph of G, that contains only the vertices in N_h^k and all the edges between them, expect those between any two vertices of the boundary set, i.e, the vertex set is N_h^k and the edge set is $\{(u,v) \in E : \ u,v \in N_h^k \text{ and } \{u,v\} \not\subseteq \partial N_h^k\}$. We will, later, call this edge-weighted subgraph the *local* *view* of h (Subsection IV-A). For brevity of notation, we define for this special sub-graph, the paths rooted at h by $P_j^{h-local} = P_{hj}^{G_h^{local}}$, $j \in N_h^k$.

B. Path Stability

For the stability metrics discussed in Subsection II-A, the stability of path p, denoted by $w(p)$, is computed by composing the link stability metrics $a(u,v)$, $(u,v) \in p$. Most of the metrics from Subsection II-A follow either additive or multiplicative compositions. Since a multiplicative composition can be transformed to an additive composition (i.e., using logarithms), we only consider additive compositions for path stability: $w(p) = \sum_{(u,v)\in p} a(u,v)$. The optimal value of the path stability metric between a vertex pair (i,j) in G' is

$$\begin{aligned} w^*_{G'}(i,j) &= \min_{p \in P_{ij}^{G'}} w(p) \\ &= \min_{p \in P_{ij}^{G'}} \sum_{(u,v)\in p} a(u,v), \end{aligned}$$

and the corresponding optimal path set, which is the set of paths that achieve the optimal value of the optimal path stability metric from i to j in the subgraph G', is

$$P_{ij}^{G'^*} = \{p \in P_{ij}^{G'} : \ w(p) = w^*_{G'}(i,j)\}.$$

In essence, computing the optimal paths corresponds to computing the shortest paths in the restricted graph G'. From hereon, we will call these shortest paths, optimal paths. We will denote the h-locally optimal paths, in G_h^{local}, from h to $j \in N_h^k$ by $P_j^{h-local^*}$.

IV. Theory of Local Pruning

Topology control by local pruning [2] in multi-hop wireless networks is an interesting graph optimization problem. These pruning algorithms make use of the local neighborhood information that is provided by neighbor discovery protocols [9]. From this local neighborhood information they select a subset of the topology that is broadcast in the network. This subset is chosen such that the resulting pruned graph preserves some properties of the original graph. The non-triviality in these problems is in establishing a relation between the local and pruned-global graph. In this section, we develop a framework to study local pruning policies that preserve the global properties of the original graph.

In [20], we extended the notion of local and global views introduced in [5] to encompass edge-weighted dynamic graphs. We summarize these extensions in the forthcoming subsections.

A. Heartbeat Discovery and Local View

We assume that every host has a neighbor discovery module [4], [10], [16]. It discovers its local neighborhood information using periodic HELLO messages. The HELLO message from each host contains both the communication adjacency and the link stability information for all of its $(k-1)$-hop neighbors ($k \geq 2$). Consequently, every host $h \in V$ discovers the dynamic edge-weighted graph G_h^{local}, where the edge-weights correspond to the symmetric link stability metrics $a(u,v)$, $(u,v) \in G_h^{local}$. In OLSR $k = 2$ because every host exchanges its one-hop link state information. This notion is formally abstracted as the *local view* G_h^{local} (Subsection III-A).

B. Pruning with Local Policies

In local pruning algorithms, the host $h \in V$, which has discovered the edge-weighted graph G_h^{local}, chooses a subset of its incident edges, which we call the *pruned edge set* of h. We denote the set of such *pruning policies* at host h by

$$F_h^{prune} = \{f : G_h^{local} \rightarrow 2^{\Omega_{G_h^{local}}(h)}\},$$

where $2^{\Omega_{G_h^{local}}(h)}$ is the power-set of $\Omega_{G_h^{local}}(h)$ (set of of all subsets of $\Omega_{G_h^{local}}(h)$).

For a given pruning policy $f_h \in F_h^{prune}$ at $h \in V$, we denote the pruned edge set by $\Omega_h = f_h(G_h^{local})$. From henceforth, f_h and Ω_h will represent the pruning policy and pruned edge set at host h respectively. Ω_h is, then, broadcast network-wide. If the subset Ω_h is small compared to $\Omega_{G_h^{local}}(h)$, then the broadcast information rate is significantly reduced. In essence, this reduced information (pruned link states) reduces the broadcast storm.

In [5], the authors show several local pruning methods, in essence, try to construct a *Connected Dominating Set* (CDS) for the dynamic graph G by local pruning. However, the CDS constructions [5], in general, do not offer guarantees on the quality of the routing paths in the pruned CDS (see Subsection II-B).

The pruning policy f_h selects a pruned edge set Ω_h and the host h broadcasts this Ω_h and their corresponding edge-weights. The corresponding broadcast edge set is given by $E^{broadcast} = \cup_{h\in V}\Omega_h$, and this induces an edge-weighted subgraph $G^{broadcast}$, which we call the *broadcast view*. At every host station $h \in V$, the *global view* G_h^{global} is the edge-weighted graph union $G_h^{local} \cup G^{broadcast}$, where G_h^{global} and $G^{broadcast}$ are exposed by some neighbor discovery and link state broadcast mechanisms respectively.

C. Expressing Global Constraints

The fundamental pruning problem for each host $h \in V$ is to construct a minimal pruned edge set Ω_h^* such that G_h^{global} preserves some desired properties of G. This is an interesting multi-agent optimization problem where the objective function (finding a minimal pruned edge set) for each agent (host) depends only on local neighborhood information (local view). However, the agents (hosts) together must satisfy a global constraint (the global view must preserve some desired properties of G). Before we consider the optimization problem (of finding the minimal pruned edge set), we will mathematically express the global constraint for stable path topology control. This is non-trivial because the global constraint involves the global view, while the hosts have access to strictly their local view. We will introduce more notation for this purpose.

For stable path routing, we want G_h^{global} to preserve all stable routing paths (of G) from h to every other vertex $j \in V$. This can be expressed as a shortest path property:

$$\pi_h^S(G) : \exists p \in {P_{(h,j)}^G}^*,\ j \in V. \quad (1)$$

Let $\Pi_h^S(G)$ denote all the subgraphs of G that contain at-least one optimal path tree rooted at h, i.e., $\pi_h^S(G)$ holds. Then the stable path preserving global constraint can be expressed as $G_h^{local} \subseteq \Pi_h^S(G)$.

Although we have mathematically expressed the global constraint for stable path pruning, this constraint cannot be directly imposed on the local view. We need local constraints that will guarantee that the global constraints are satisfied. Since the local pruning policies of interest at host $h \in V$ are given by the functions $f_h \in F_h^{prune}$, we will consider a class of pruning functions and show that they satisfy the global constraint.

We define a local property $\pi_h^{\Omega-S}$ at $h \in V$. Given the local view G_h^{local}, the property $\pi_h^{\Omega-S}(G_h^{local})$ is said to hold for a pruning policy $f_h \in F_h^{prune}$ if for all $j \in \partial N_h^k$ there exists a path $p \in P_j^{h-local^*}$ such that $(h, \eta_p^h) \in f_h(G_h^{local})$. Let $\Pi_h^{\Omega-S}(G_h^{local})$ denote the subset of policies (of F_h^{prune}) for which $\pi_h^{\Omega-S}(G_h^{local})$ holds. Clearly, the property $\pi_h^{\Omega-S}$ is local because it depends on only G_h^{local}. This local constraint, in essence, requires for every host h to select an incident edge on at-least one locally optimal path to every boundary node in ∂N_h^k.

To understand the intuition behind this local policy, consider a line graph shown in Figure 2, where all edge-weights are 1. Let the size of the neighborhood be $k = 2$. Clearly, in this example, only the hosts h_2 and h_3 are responsible of selecting (h_2, h_3) (by the virtue of the local pruning policy in Subsection IV-B). Let us consider the pruning policy at h_2. Here, $\partial N_{h_2}^k = \{h_4\}$. (h_2, h_3, h_4) is the only path from h_2 to h_4. And, $\partial N_{h_3}^k = \{h_1, h_5\}$. (h_3, h_2, h_1) is the only path from h_3 to h_1. If $(h_2, h_3) \notin \Omega_{h_2}$ and $(h_3, h_2) \notin \Omega_{h_3}$, then $(h_2, h_3) \notin G^{broadcast}$. Since $(h_2, h_3) \notin G_{h_5}^{local}$, $(h_2, h_3) \notin G_{h_5}^{global}$. Consequently, $G_{h_5}^{global}$ does not contain the globally optimal paths to h_1 and h_2.

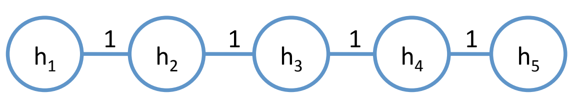

Fig. 2: Example line graph illustrating the local pruning condition

However, this local condition is not sufficient to ensure $G_h^{global} \in \Pi_h^S(G)$, since it does not guarantee *loop-freedom*. This is a well-known problem for distributed routing protocols [21]: Loops typically occur in distributed graph algorithms when tie-breaking mechanisms are not employed. Using an example, we illustrate that a similar problem is likely to occur in stable path distributed pruning without tie-breaking.

Consider an example edge-weighted graph shown in Figure 3, where the edge-weights correspond to some link stability metric (Section II). Consider any stable path pruning policy at stations $h_1, h_2, \ldots, h_5$. Let the size of the neighborhood exposed be $k = 2$. The neighborhood boundary sets are $\partial N_{h_1}^2 = \{h_3\}$, $\partial N_{h_2}^2 = \{h_4\}$, $\partial N_{h_3}^2 = \{h_1\}$, $\partial N_{h_4}^2 = \{h_2, h_5\}$ and $\partial N_{h_5}^2 = \{h_4\}$. If the pruning mechanisms at these stations satisfy the necessary conditions, then station h_4 choses (h_4, h_3) and station h_5 choses (h_5, h_3). However, the pruning mechanisms at stations h_1, h_2 and h_3 have multiple optimal paths to choose from. For station h_1 to reach h_3, there are two optimal paths, (h_1, h_2, h_3) and (h_1, h_5, h_3). For station h_2 to reach h_4, there are two optimal paths, (h_2, h_3, h_4) and $(h_2, h_1, h_5, h_3, h_4)$. For station h_3 to reach h_1, there are two optimal paths, (h_3, h_2, h_1) and (h_3, h_5, h_1). The Figure 3 illustrates one pruning policy that satisfies the necessary conditions: h_1 chooses (h_1, h_2) for path (h_1, h_2, h_3), h_2 chooses (h_2, h_1) for path $(h_2, h_1, h_5, h_3, h_4)$, and h_3 chooses (h_3, h_5) for path (h_3, h_5, h_1). The pruned graph $G^{broadcast}$, shown in the Figure 3, is then disconnected! Clearly, the distributed pruning does not preserve the stable optimal paths in the different global views.

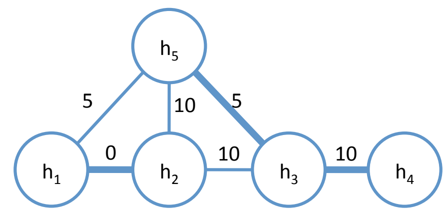

Fig. 3: An example to illustrate loops in pruning

D. Positivity Assumption and Sufficiency

The example of Figure 3 suggests a sufficient condition, which we call the *positivity condition*: all the edge weights are strictly positive, $a(u, v) > 0,\ (u, v) \in E$. We will show that under the positivity assumptions, the local pruning conditions become sufficient.

Theorem 4.1: Under the positivity assumption, if $h \in V$, $f_h \in \Pi_h^{\Omega-S}(G_h^{local})$, then $G_h^{global} \in \Pi_h^S(G)$.
Due to space limitations, we omit the proof in this paper. For the proof, see [11].

E. Optimal Pruning as a Local Set-Cover Problem

In the previous section, we showed sufficient conditions for preserving global stable paths. In this section, we formulate the pruning problem as an optimization problem subject to the local pruning constraints. Every host $h \in V$ given only its *local view* solves for a minimal pruned edge set:

$$\min_{f_h \in \Pi_h^{\Omega-S}(G_h^{local})} |\Omega_h| \quad (2)$$

Attempting to list out all feasible pruning policies $f_h \in \Pi_h^{\Omega-S}(G_h^{local})$, in general, is computationally intractable. However, the additive path stability metric follows Bellman's optimality principle [11], and consequently, can be efficiently computed. Let $\zeta_h : \partial N_h^1 \rightarrow 2^{\partial N_h^k}$ denote the covering function: for $i \in \partial N_h^1$ and

$$\zeta_h(i) = \{j \in \partial N_h^k : \exists p \in P_j^{h-local*} \text{ such that } i = \nu_p^h\}.$$

The corresponding inverse $\zeta_h^{-1} : \partial N_h^k \rightarrow 2^{\partial N_h^1}$ is: for $j \in \partial N_h^k$

$$\zeta_h^{-1}(j) = \{i \in \partial N_h^1 : j \in \zeta_h(i)\}.$$

This function ζ_h can be computed efficiently using any shortest path procedures [19] (see Section [11]). Then local pruning problem of Eqn. 2 can be posed as a set-cover problem:

$$\min_{\Delta \in 2^{\partial N_h^1}} \quad |\Delta| \qquad (3)$$
$$\text{subject to} \quad \cup_{i \in \Delta} \zeta_h(i) = \partial N_h^k.$$

Theorem 4.2: For any minimizer Δ^* in Equation (3), $\{(h,i) : i \in \Delta^*\}$ solves the minimal pruning problem of Equation (2).
Again, due space limitations, we omit the proof. See [11] for the proof.

Note that with increasing local neighborhood size k, the size of the optimal cover δ^* will be smaller. This implies that with increasing k, the algorithms can prune more of the local topology. However, this comes at the cost of a larger neighborhood discovery.

V. Stable Path Topology Control Algorithm

In this section, we present the Stable Path Topology Control (SPTC) algorithm that solves the set-cover problem (to an approximation) in Equation (3). Finally, we demonstrate the performance of the SPTC algorithm by using the ETX metric (discussed in Subsection II-A).

A. Greedy Approximation Algorithm to Solve Set-Cover Problem

Given ζ_h, Algorithm 1 is a greedy algorithm that approximately solves Equation (3).

Let $d_h^* = \max_{i \in \partial N_h^1} |\zeta_h(i)|$. Then the following lemma gives the approximation bounds for the greedy solution $R_{h-greedy}$:

Lemma 5.1: Let the optimal solution to Equation (3) be Δ_h^* and $R_{h-greedy}$ be the output of Algorithm 1 at host h, then $|R_{h-greedy}| \leq H(d^*)|\Delta_h^*|$, where $H(N) = \sum_{n=1}^{N} \frac{1}{n}$.

This lemma is proved in Chapter 11 of [19].

B. Simulation Resuts

All simulations were carried out in OPNET Modeler 14.5 [22]. The parameters of the simulation and the different modifications to the OLSR code are reported in our technical report [11]. From the simulations, we compare both the data traffic carrying and Topology Control (TC) overhead performance of SPTC-ETX and OLSR-ETX. Due to the space limitation, we present the result for only the simple topology shown in Figure 4 (Results for more realistic and complex topologies are presented in our technical report [11]). This scenario corresponds to the example topology in Subsection II-B that illustrates the fundamental limitation of CDS constructions. The topology is set up such that there is a long-distance unstable wireless between *manet_0* and *manet_1*. All other links are short and hence more stable compared to *(manet_0,manet_1)*.

Algorithm 1 Greedy Set-Cover Algorithm at h

INPUT: $\zeta_h, G_h, \partial N_h^1, \partial N_h^k$
Init: $R_{h-greedy} \leftarrow \emptyset$, $U \leftarrow \partial N_h^k$;

// Find and append essential cover elements
for all $\{j \in \partial N_h^k : |\zeta_h^{-1}(j)| = 1\}$ **do**
  $R_{h-greedy} \leftarrow R_{h-greedy} \cup \zeta_h^{-1}(j)$;
  $U \leftarrow U \backslash \{j\}$;
end for

// Greedy selection
while $U \neq \emptyset$ **do**
  $i^* \leftarrow \arg\max_{i \in \partial N_h^1} |\{j \in U : j \in \zeta_h(i)\}|$
  $R_{h-greedy} \leftarrow R_{h-greedy} \cup \{i^*\}$
  $U \leftarrow U \backslash \{j \in U : i^* \in \zeta_h(j)\}$
end while
Output: $R_{h-greedy}$

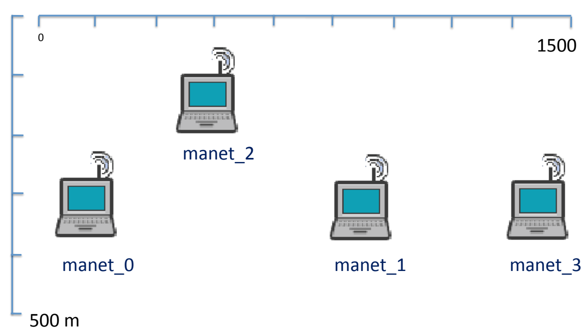

Fig. 4: 4 node topology to illustrate the limitation of CDS constructions

Consider OLSR-ETX MPR selection process at node *manet_0*. Since the link *(manet_0,manet_1)* is unstable, it goes ON and OFF frequently. Whenever this link is ON, *manet_3* $\in \partial N^2_{manet_0}$. The OLSR-ETX set-cover construction selects the unstable link *(manet_0,manet_1)* as Ω_{manet_0} because it the only edge in the two-hop path to reach *manet_3*. When the link *(manet_0,manet_1)* is OFF, *manet_1* $\in \partial N^2_{manet\_0}$, and consequently, OLSR-ETX chooses *(manet_0,manet_2)* as Ω_{manet_0}. Thus as the unstable link *(manet_0,manet_1)* goes ON and OFF, Ω_{manet_0} oscillates between *(manet_0,manet_1)* and *(manet_0,manet_2)*. This is shown in Figure 5, which is the topology selection process at *manet_0* obtained from one of the OPNET simulation runs.

Fundamental limitation of the set-cover OLSR construction is that it is not designed to exploit the local path diversity. This limitation is overcome by the SPTC-ETX that provides a more stable Ω_{manet_0}. From simulations we observed that SPTC-ETX almost always chooses $\Omega_{manet\_0} = \{(manet\_0, manet\_2)\}$ and $\Omega_{manet\_2} = \{(manet\_2, manet\_1)\}$, thus preserving the stable path *(manet_0,manet_2,manet_1)*. For a simulation period of 1 *hour*, we observed 96 topology changes for OLSR-ETX and only 6 for SPTC-ETX on an average.

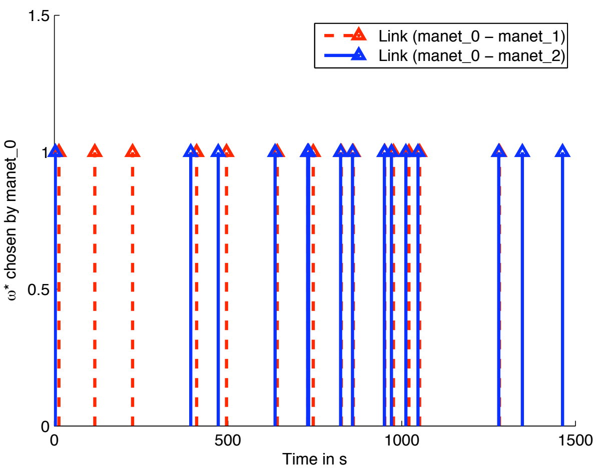

Fig. 5: Topology selection process at manet_0 for OLSR-ETX

We report the simulation results characterizing the traffic carrying performance and topology control overheard for several realistic scenarios in [11]. We observe that the SPTC-ETX outperforms OLSR-ETX, in both the performance metrics, for all the scenarios considered [11].

VI. Conclusion

In this paper, we introduced a new topology control problem for preserving stable routing paths. We formulated the problem as a constrained multi-agent optimization problem with only local neighborhood information. We established sufficient conditions that reduce the global pruning constraint to a local constraint on the pruning policies. We presented the SPTC algorithm that approximately solves the stable path topology control problem. Finally, we quantified the two-fold advantage of SPTC with different simulation scenarios: by using the popular ETX metric, we showed that the topology formed by SPTC-ETX is stable and is able to carry significantly higher traffic compared to OLSR-ETX.

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