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An Overlay Architecture for Throughput Optimal Multipath Routing

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Abstract:- Legacy networks are often designed to operate with simple single-path routing, like the shortest path, which is known to be throughput suboptimal. On the other hand, previously proposed throughput optimal policies (i.e., backpressure) require every device in the network to make dynamic routing decisions. In this paper, we study an overlay architecture for dynamic routing, such that only a subset of devices (overlay nodes) need to make the dynamic routing decisions. We determine the essential collection of nodes that must bifurcate traffic for achieving the maximum multi-commodity network throughput.

Key Words:- Single-Path Routing, Backpressure, Dynamic Routing & Bifurcate Traffic.

1.INTRODUCTION

Optimal routing in networks where some legacy nodes are replaced with overlay nodes. While the legacy nodes perform only forwarding on pre-specified paths, the overlay nodes are able to dynamically route packets. Dynamic backpressure is known to be an optimal routing policy, but it typically requires a homogeneous network, where all nodes participate in control decisions. Instead, we assume that only a subset of the nodes are controllable; these nodes form a network overlay within the legacy network. The choice of the overlay nodes is shown to determine the throughput gio of the network. Since standard backpressure routing cannot be directly applied to the overlay setting, we develop extensions to back-pressure routing that determine how to route packets between overlay nodes. We confirm that maximum throughput can be attained with our policies in several scenarios, when only a fraction of legacy nodes are replaced by controllable nodes. Moreover, we observe reduced delay relative to the case where all nodes are controllable and operate under backpressure routing.

A. Motivation and Related Work

Back pressure(BP) routing, first proposed in[16],is a throughput optimal routing policy that has been studied for decades. Its strength lies in discovering multipath routes and utilizing them optimally without knowledge of the network parameters, such as arrival rates, link capacities, mobility, fading, etc. Nevertheless, the adoption of this routing policy has not been embraced for general use on the Internet. This is due, in part, to an inability of backpressure routing to coexist with legacy routing protocols. With few exceptions, back-pressure routing has been studied in homogeneous networks, where all nodes are dynamically controllable and implement the back pressure policy across all nodes uniformly.

B. Problem Statement and Contributions

We consider two problem areas for control of heterogeneous networks. First, we develop algorithms for choosing the placement of controllable nodes, where our goal here is to allocate the minimum number of controllable nodes such that the full network stability region is available. Second, given any subset of nodes that are controllable, we also wish to develop an optimal routing policy that operates solely on these nodes.

2. DESIGN

We model the network as a directed graph G = (N ,E), where is the set of nodes in the network and is the set of edges. We assume that the underlay network provides a fixed realization for shortest-path routes between all pairs of nodes, and that uncontrollable nodes will forward traffic only along the given shortest-path routes. Further, we assume path from a to b, Pab, where is a controllable node and v is the only node shared between shortest-paths P SP and P SP. Note that a 2-concatenation of a cyclic paths will always be acyclic, as we only allow the concatenated paths to share the overlay node v at which concatenation is performed. An n-concatenation is then the concatenation of n shortest- paths at n 1 controllable nodes, performed as a succession of(n 1) 2-concatenations, and is therefore acyclic. Consider the set of paths which contains all underlay paths SP as well as all possible n-concatenations of these paths at the controllable nodes .We will see that this set plays a role in the achievability of the throughput region. we only allow the concatenated paths to share the overlay node *v* at which concatenation is performed. An *n-concatenation* is then the concatenation of *n* shortest-paths at (*n 1)*controllable nodes, performed as a succession of (*n*1) 2-concatenations, and is therefore acyclic. Consider the set of paths , which contains all underlay paths ^{SP}as well as all possible *n*-concatenations of these paths at the controllable nodes .We will see that this set plays a role in the achievability of the throughput region.

3. ANALYSIS

A. Problem Statement and Contributions

We consider two problem areas for control of heterogeneous networks. First, we develop algorithms for choosing the placement of controllable nodes, where our goalNhere is to allocate the minimum number of controllable nodes such that the full network stability region is available. Second, given any subset of nodes that are controllable, we also wish to develop an optimal routing policy that operates solely on these nodes. In the first problem area, we are given a graph *G* with nodes supporting shortest-path routes between each pair of nodes. We wish to identify a minimal set of controllable nodessuch that if only these nodes are allowed to bifurcate traffic, maximum throughput can be achieved. Ideally, we would like to solve P1,path from *a* to *b*, P_{ab}, where *v* is a controllable node and *v* is the only nodes hared between shortest-paths P^{SP} and P^{SP}. Note that a2 concatenation of a cyclic paths will always be acyclic, as we only allow the concatenated paths to share the overlay node *v* at which concatenation is performed. An *n-concatenation* is then the concatenation of *n* shortest-paths at *n* 1controllable nodes, performed as a succession of (*n*1) 2-concatenations, and is therefore acyclic. Consider the set of paths , which contains all underlay paths ^{SP} as well as all possible *n*-concatenations of these path sat the controllable nodes. We will see that this set plays a role in the achievability of the throughput region. Used in isolation; our node placement algorithm can be used with other control policies, and our BP extensions can yield maximal stability with any over lay node placement and legacy single-path routing.

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Our contributions are summarized below. We formulate the problem of placing the minimum number of overlay(controllable) nodes in a legacy network

OVERLAY NODES IN WIRELESS NETWORKS

The goal is to motivate the need for additional study into the placement of overlay nodes for networks with wireless interference. The all-paths condition C.1 is sufficient to achieve ΛG( ) = ΛG in all networks, but this condition is not always a necessary condition in wireless networks. In other words, satisfying the all-paths condition may over allocate controllable nodes under certain wireless interference models. To see this, consider a clique where all edges have unit-capacity and all transmissions mutually interfere.

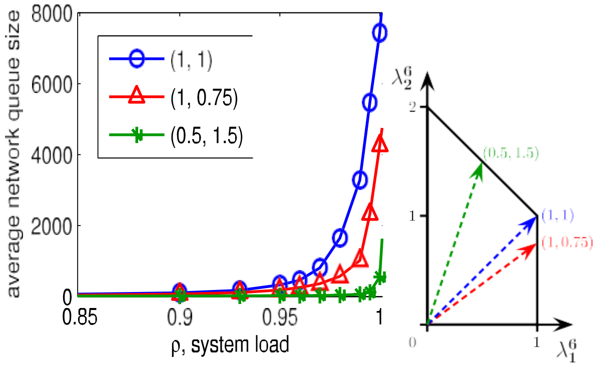

Figure:- a) Simulation results & b)Throughput region

Comparing OBP with BP on a random graph. (a) Scenario with two symmetric traffic demands. (b) Average queue size for BP, BP+SP, and OBP delay performance when there are few controllable nodes. In this particular example, only the source is controllable, with n 1 legacy nodes, a setting that corresponds to the maximum benefit. Delay is compared between BP and OBP for a fixed offered load in Fig. 13b and for a fixed number of nodes in Fig. 13c. Although BP is applied at all nodes it is still outperformed by OBP applied only at the source.

Finally, in Fig. above, we show simulation results from three policies: OBP, BP at all nodes, and BP with shortest-path bias (BP+SP) from [9].Although the latter two are both throughput optimal policies, they yield worse delay than OBP. The reason is threefold:(i) the quadratic network queue size of BP is proportional to the number of controllable nodes used (in this scenario, OBP uses only 5 overlay nodes), (ii) no packets are sent to attached trees in case of OBP, and (iii) under light traffic, packets under BP perform random walks.

Finally, we consider the performance of OBP on a ring network with N = 20 nodes and V = 3 overlay nodes, where V = 3 was proved sufficient to achieve ΛG( ) = ΛG by Lemma 5. The scenario is shown in Fig. 15a, with two competing traffic demands indicated with red arrows. Fig. 15b shows the throughput region for these two traffic demands, with 4 rate vectors identified, and results for the OBP policy on these rate vectors is shown in Fig. 15c. For each rate vector, we see the queues remain small for all points internal to the throughput region, indicating that OBP can stabilize the system for these vectors.

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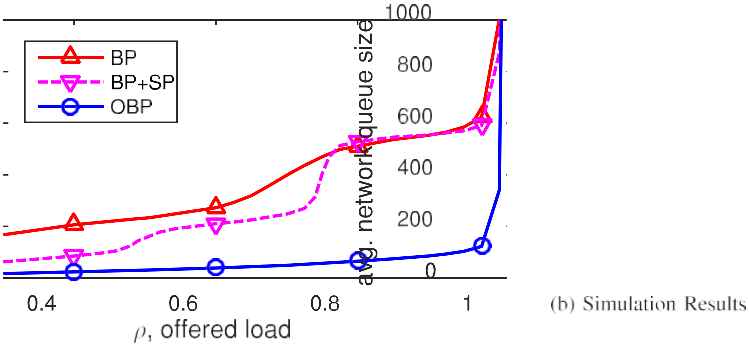
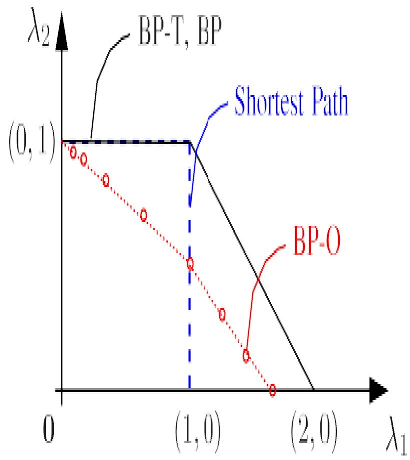


Comparing OBP with BP on a random graph.
(a) Scenario with two symmetric traffic demands. (b)Average queue size for BP, BP+SP, and OBP.

delay performance when there are few controllable nodes. In this particular example, only the source iscontrollable,with*n*1 legacy nodes, a setting that corresponds to the maximum benefit. Delay is compared between BP and OBP for a fixed offered loadinFig.13bandforafixednumber of nodes in Fig. 13c. Although BP is applied at all nodes it is still out performed by OBP applied only at the source



Throughput comparison of routing schemes: BP-T,BP-O,ShortestPath,andBP.

a tunnel if $F_{ij}(t) \geq T$.Therefore, when tunnels do not overlap, the total tunnel backlog is limited to at most $T + R_{\max}$, where $R_{\max}$ is the maximum number of packets that may enter the tunnel in one slot. Thus, the threshold-based policy keeps the tunnel occupancy bounded, and ensures that when the tunnel is full, a minimum rate of flow out of the tunnel is guaranteed. It is the combination of these two conditions that guarantees the throughput optimality of BP-T when tunnels do not overlap.

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OPTIMALNODEPLACEMENTEXAMPLES

We provide results for various types of network graphs, including specific graph families and random graphs. By Theorem 1, the full throughput region is provided by the placement of our algorithm on all these cases.

1) automatically satisfied, and $\Lambda_G()=\Lambda_G()$.
Itfollowsthatnocontrollablenodesarerequiredforaforest,whichisadisjointunionoftrees.

Lemma5: Exactly 3 controllable nodes are required to satisfy the all-paths condition for a ring network with N5 nodes and hop-count as the metric for shortest-path routing. This is proved by showing that shortest-paths exist from any node to at least N/3 other nodes in each direction around the ring. Thus, there exists a placement of 3 controllable nodes that can satisfy By optimal substructure, the union of shortest-paths P^{SP} to any destination n from all nodes x n forms destination tree D_n. Destination trees D_n are shown for the example graph in Fig.3c.Define P^{SP} n to be these to f nodes on the shortest path from x to n, excluding node. Thus, we have P3.By Theorem1,there main in g assertions follow.Phases1-2of the algorithm have complexity $O(N^2)$.P4 solve saver t ex cover problem, which is known to be NP-Hardin general. However, note that the constraints of our problem have optimal substructure, which might be exploitable. For our experiments on graphs with 1000 nodes, the solver found most solutions to P4 within 5seconds, and we only rarely encountered scenarios that required more than a few minutes to solve. Thus, the algorithm is practical. Program P4 is intended to be used offline to find an optimal node placement. If an online solution is desired with a polynomially bounded runtime, then the following algorithm can be used in place of P4 for each disjoint graph in G'. Let $V=\varnothing$,mark all nodes as un visited, and create a to Every node in G' will the neither be included in or will be on at least one pruned tree D'_V :v, Each of N nodes can be marked at most once, and the marked status of each node can be tested O(N) times, yielding a complexity of $O(N^2)$.This is proved by showing that every path is either(i)a shortest path or(ii)can be formed as a concatenation of shortest paths at overlay nodes which satisfy the leaf node constraint of P4. The proof of Lemma 3 is available in[6].The following main result establishes the performance of the proposed placement algorithm. Theorem 2: Let be the solution produced by the overlay node placement algorithm. Then, $*$ is an optimal solution to P3.It follows that $\Lambda_G(V^*)=\Lambda_G$. is an optimal solution to P1.

Cycles and Rings:

Lemma 4: Everycyclerequiresatleast3controllablenodestosatisfytheall-pathscondition.

For a ring, observe that shortest path P_{ab}^{SP} connects nodes *a* and *b* in only one direction, even when *a* and *b* are themselves controllable. At least one more controllable node is required to form path $P_{ab} P^{SP}$ in the counter direction a K_{ab}-slot Lyapunov drift analysis. The proof details can be found in[11].

We simulate the BP-T scheme on the simple network topology of Fig. 8, where we define two sessions sourced at *a*; session 1 destined to *e* and session 2 to *c*. We assume that R_{ab}=2andallotherlinks have unit capacity as shown in the figure.

A. Overlay Back pressure Heuristic Algorithm

Although we are able to show that the BP-T is through put optimal when tunnels do not overlap ,its performance in the general case of overlapping tunnels is not guaranteed. Nonetheless, simulation results on simple overlapping tunnel topologies indicate good throughput performance even when tunnels overlap [12]. In this section, we propose a heuristic scheme that is inspired by BP-T, yet is much

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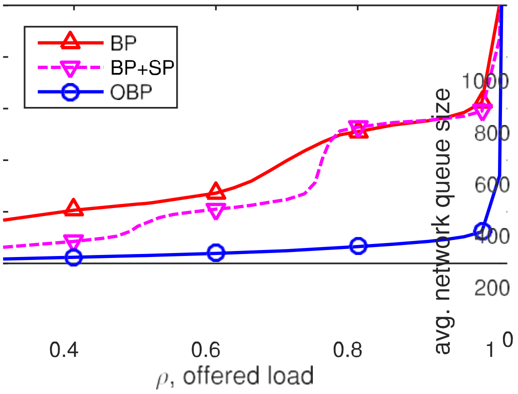
simpler to implement. In particular, our heuristic takes tunnel congestion into account, but does not require the threshold computation and associated knowledge of the underlay topology.

1) *Overlay Backpressure (OBP):* Redefine the differential backlog as,



(b) Simulation Results

Comparing OBP with BP on a random graph.(a) Scenario with two symmetric traffic demands.(b)Average queue size for BP,BP+SP, and OBP. delay performance when there are few controllable nodes. In this particular example, only the source is controllable, with *n*1 legacy nodes, a setting that corresponds to the maximum benefit. Delay is compared between BP and OBP for a fixed offered loadinFig.13bandforafixednumber of nodes in Fig. 13c. Although BP is applied at all nodes it is still out performed by OBP applied only at the source.
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4.RESULTS

Although we are able to show that the BP-T is through put optimal when tunnels do not overlap ,it s performance in the general case of overlapping tunnels is not guaranteed. Nonetheless, simulation results on simple overlapping tunnel topologies indicate good throughput performance even when tunnels overlap [12]. In this section, we propose a heuristic scheme that is inspired by BP-T, yet is much simpler to implement. In particular, our heuristic takes tunnel congestion into account, but does not require the threshold computation and associated knowledge of the underlay topology.

5. CONCLUSIONS

We study optimal routing in legacy networks where only a subset of nodes can make dynamic routing decisions, while the legacy nodes can forward packets only on pre-specified shortest-paths. This model captures evolving heterogeneous networks where intelligence is introduced at a fraction of nodes. We propose a necessary and sufficient condition for the overlay node placement to enable the full multi commodity throughput region. Based on this condition, we devise an algorithm for optimal controllable node placement. We run the algorithm on large random graphs to show that very often a small number of intelligent nodes suffices for full throughput. Finally, we propose dynamic routing policies to be implemented in a network overlay.

6.REFERENCES

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