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A Case for Joint Routing, Scheduling, and Network Coding in TDMA-based Wireless Mesh Networks: A Cross-layer Approach

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Abstract—**Network coding has been successfully applied to contemporary Wireless Mesh Networks (WMNs) to reduce intra-network interference and enhance the capacity of the WMN. State-of-the-art WMNs, however, introduce features such as explicit per-link bandwidth reservation and per-link encryption, which make the application of prior network coding approaches in these WMNs suboptimal, if not impossible. In this paper we look at the above challenge from a new perspective and present efficient heuristics for tackling the joint QoS routing, scheduling, and network coding problem. An experimental evaluation shows that the designed heuristics are able to yield excellent solutions in real-time, even if we assume dynamically changing traffic in the WMN.**

I. INTRODUCTION

Intra-network interference, i.e. interference in the network caused by the network, is one the most important capacity limiting factors [1] in WMNs (see [2] for a survey on WMNs). Recent developments in the field of network coding (see Refs. [3], [4]) have demonstrated the potential of network coding and its application for maximizing the transport capacity of WMNs. Network coding has been applied successfully in WMNs based on IEEE 802.11 like Medium Access Control (MAC) layers (see [5]). Network coding thus promises to be a vital tool which can be used to reduce intra-network interference (by reducing the number of transmissions required) thereby freeing up bandwidth for additional traffic (this can be seen as an increase in the traffic carrying capacity of the WMN compared to traditional approaches). However, recently developed standards for WMNs such as IEEE 802.16 [6] or IEEE 802.11s are fundamentally different from the contemporary IEEE 802.11 MAC layer. Bandwidth reservation schemes to support per-link QoS and per-link encryption to enhance security in WMNs are some novel features introduced by the newer class of MAC standards for WMNs. These advanced features make the application of network coding in WMNs as described in the prior literature difficult, if not impossible.

Thus it is necessary to investigate the performance gains that can be obtained using network coding for maximizing the traffic carrying capacity in such WMNs from a new perspective. Moreover, we are also interested in considering the QoS requirements of the traffic to be carried over the network in parallel with maximizing the network capacity. This adds another challenging dimension to the problem under consideration.

In this paper, without loss of generality and to put our discussion in concrete settings, we assume that the WMN uses the IEEE 802.16-2004 standard. In particular the WMN is assumed to use the MeSH[1] mode specification. The MeSH mode, similar to the 802.11s proposal, uses Time Division Multiple Access (TDMA) with Time Division Duplex (TDD) to support QoS on the MAC layer and enable the provision of carrier-grade QoS. Further, to ensure secure communication, the MeSH mode specifies per-link encryption at the MAC layer. Thus, the MeSH mode can be considered to be a representative for state-of-the-art MAC layers for WMNs. At this stage we would recommend that the readers not familiar with the MeSH mode specifications consult some introductory literature on the MeSH mode to enable them to follow the discussion with additional ease (e.g. Refs. [7], [6]).

II. QOS ROUTING, SCHEDULING, AND NETWORK CODING AS A JOINT PROBLEM

Routing and scheduling in wireless networks are closely interdependent as the chosen routes affect the possible schedules and vice versa. The authors in [8] consider the above routing and scheduling problem and optimize the two jointly. However, unlike our problem, they assume simpler scheduling mechanisms and consider neither network coding issues nor QoS constraints.

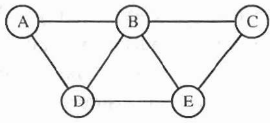

Fig. 1. Toy topology to motivate the research problem

The following example motivates the research problem. Let us consider the simple topology shown in Fig. 1. Assume that the QoS metric is hop-count, and that the QoS specification requires that the flows be routed along the shortest path or longer paths having at most a permitted number of additional hops (for the following example consider that at most two additional hops are permitted). Assume that we have flows between the (*source,destination*) pairs (A,C) and (E,A). Let us also assume that the default shortest hop paths found per pair are as follows, (A,C): $A \rightarrow B \rightarrow C$, and ($E$,$A$): $E \rightarrow B \rightarrow A$.

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[1] Throughout this document we use the notation MeSH to denote the mesh mode of the IEEE 802.16-2004 standard.

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In the above constellation, the routes make heavy use of the highly-connected node B leading to quite a large number of blocked links per transmission to or from node B. A transmission scheduled on a given link is said to block other links if no simultaneous transmissions may be scheduled for the latter links. The more the number of links blocked the fewer the number of slots available for scheduling additional data transmissions in parallel on other links. This implies a reduced data carrying capacity for the network.

On the other hand, if we have encrypted links as in the MeSH mode (i.e. transmissions on a link can be decoded only by the intended receiver(s)), it is obvious that it is not possible to deploy network coding even in the simple "Alice↔Relay↔Bob" configuration used as a motivational example by the authors in [5]. Thus, no gain can be obtained from the deployment of network coding in the WMN.

In summary, using the best (shortest) QoS paths may lead to high intra-network interference and it is also not possible to optimally utilize the potential of novel mechanisms such as network coding, which otherwise may help to enhance the traffic carrying capacities of the network (see Refs. [5], [3]).

In the above example, considering the QoS constraints, the network provider may decide to reroute some (or all) the flows to achieve (1) less interference, i.e. lower number of blocked links (or less number of timeslots in a TDMA system to support the same traffic), and (2) enable opposing traffic flows so that even in the presence of encrypted links, simple network coding in the "Alice↔Relay↔Bob" configuration can be supported, thereby further freeing up timeslots for transmission. This is the core motivation for the work presented here.

To illustrate this we will further use the above example. Consider that we now have the same flows, however, we now route them as follows, (A,C): $A \rightarrow D \rightarrow E \rightarrow C$, and (E,A):$E \rightarrow D \rightarrow A$. Here, the flow (A,C) no longer uses the shortest path, but still a path permitted by the QoS requirements. However, by this rerouting, we have now avoided the highly-connected node B, and simultaneously enabled the use of network coding in the "Alice↔Relay↔Bob" configuration "$A \leftrightarrow D \leftrightarrow E$". We see that a naïve approach optimizing routing, network coding, and scheduling separately, is not optimal. Scheduling also needs to be considered simultaneously as one needs to check that a transmission schedule can be computed for the network such that the traffic demands are met. Thus, we see that if one jointly considers the routing, schedule and network coding it is possible to enhance the throughput of the network without neglecting the QoS constraints.

In the next section we present our solution approach to address the above issue in state-of-the-art WMNs such as those based on the MeSH mode.

III. JOINT NEAR-OPTIMAL ROUTING, SCHEDULING, AND NETWORK CODING

The solution we present is tailored to suit the needs of state-of-the-art WMNs using TDMA/TDD and deploying per-link encryption similar to the MeSH mode specification. We modeled the problem as a Mixed Integer Programming (MIP) problem and used GLPK [9] to solve it. For small problem sizes, (few nodes, few traffic flows, and only a few timeslots per frame), results are obtained within an acceptable duration of time. However, even for moderate network sizes, (e.g. 16 nodes with more than 5 flows and more than 10 timeslots), the time required to compute the solution was more than 24 hours, which is not acceptable for online, runtime optimization. Our goal is to optimize, in real-time; routing, scheduling, and network coding jointly in presence of changing traffic demands.

We therefore designed a heuristics based solution to the above problem. We split the problem into three parts (1) QoS Route Preselection (QoSRPS) (2) Optimum QoS Route Combination (OptQoSRC) and (3) Maximal Scheduling (MaxSch). Due to space limitations we only present an overview of each heuristic. Our solution framework assumes the presence of a special node (hereafter referred to as MBS) which is responsible for periodically reviewing the traffic situation in the WMN and using the heuristics for the problems (1–3) to optimally manage the bandwidth. In WMNs using the MeSH mode this node will typically be the mesh base station, which is also responsible for admission control and allowing new flows in the network. Thus, this node will periodically receive information about the QoS requirements and the traffic demand. We next highlight the role of each of the above (1–3) heuristics. All the heuristics are run by the MBS.

QoSRPS Heuristic:

At the MBS, information about the QoS requirements of flows is used to precompute a set of feasible routes per flow. QoSRPS introduces a parameter (dynamically settable by the network operator) limiting the number of routes computed per flow.

OptQoSRC Heuristic:

The MBS uses the information it has and the routes computed using QoSRPS to find an optimal tuple of routes, at most one route per flow in the network. No route may be found for a flow if it is not schedulable. The heuristics OptQoSRC and MaxSch work together, with MaxSch being used as a subroutine by OptQoSRC to check the schedulability of flows for the selected tuple of routes. The OptQoSRC heuristic is parametrizable and the network operator can influence the computing time available to OptQoSRC for finding an optimal combination of routes — optimal with respect to QoS, number of blocked links, and the timeslots which can be additionally saved due to gained network coding opportunities. Internally, the OptQoSRC heuristic uses a binary search mechanism to find a set of routes for a subset of flows which can be scheduled optimally.

MaxSch Heuristic:

The MaxSch heuristic computes a maximal schedule for the given set of flows, their individual traffic demands, and their corresponding routes selected by the OptQoSRC heuristic. Our MaxSch heuristic is similar to the approach presented in [10] and additionally considers network coding.

The WMN can use any routing protocol to populate routing tables at individual nodes. The MBS sends routing table updates to nodes based on the optimal routes computed using the above heuristics. The MBS also initiates advance reservation/allocation of bandwidth along the new routes and the freeing of bandwidth along routes which are no longer used. In the next section we present some proof-of-concept results obtained by using our solution framework in an IEEE 802.16-2004 based WMN deploying distributed scheduling.

IV. PROOF-OF-CONCEPT REALIZATION AND RESULTS

As a proof-of-concept, we implemented our solution framework in a WMN using the MeSH mode within an IEEE 802.16 mesh simulator built up on top of a consolidated version of JiST/SWANS [11]. The simulations used the ETSI (n=8/7, 3.5 MHz, OFDM 256) mode of the IEEE 802.16-2004 standard. The frame duration is set to 10 ms. The total number of timeslots available for data transmission in a frame was 98. From the timeslots available our heuristics were allowed to use up to 70 slots, reserving the remaining for smaller flows and short term data bursts, which cannot be centrally scheduled optimally given real-time constraints.

The network topology we consider here is the same as shown in Fig. 1. The flows in the network are Flow 1:(A,C) starting at time 10 sec and stopping at 20 sec with a constant data rate (demand) equivalent to 6 timeslots per frame; and Flow 2:(E,A) starting at 13 sec and stopping at 17 sec with a demand equivalent to 11 timeslots per frame.

Initially, Flow 1 is routed via the path $A \rightarrow B \rightarrow C$ which is the minimum interference path and also the best QoS path. After the initial bandwidth requests have been processed, the end-to-end delay for Flow 1 is approximately equal to the minimum achievable delay (assuming data cannot be forwarded in the frame in which it is received), i.e. 20ms (① in Fig. 2). When Flow 2 starts at time $t = 13s$, the OptQoSRC heuristic detects that the overall minimum interference route set uses route $A \rightarrow D \rightarrow E \rightarrow C$ for Flow 1 and $E \rightarrow D \rightarrow A$ for Flow 2. Although the path length for Flow 1 increases by one hop, the rerouting of this flow helps to reduce the overall interference by allowing node D to act as network coding relay for nodes A and E. Due to advance bandwidth reservation carried out by our solution framework, the transition from one path to the other is smooth. The delay for Flow 3 increases to 30ms (② in Fig. 2) since now three hops are needed for this flow. As Flow 2 ceases at $t = 17$s, Flow 1 is rerouted back to its default path (③ in Fig. 2). Additional results and details are presented in the poster corresponding to this paper.

V. CONCLUSION

The results presented here, in the poster, and additional experiments demonstrate that our heuristics are able to achieve excellent results given realistic assumptions for the WMN and also considering features introduced by state-of-the-art WMN. Flows are rerouted in order to free network capacity whereby network coding opportunities are detected and used. Once a flow is admitted by the MBS, the flow's end-to-end delay drops to values that correlate with the route length of the flow. Due to the constant bandwidth reservations used the delay remains nearly constant, even if other flows lead to a congestion of a node on the route.

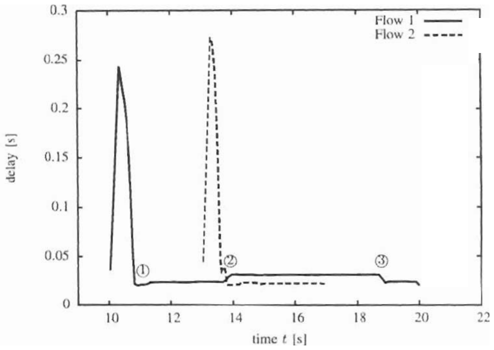

Fig. 2. End-to-end delays for the toy topology from Fig. 1

Requesting bandwidth before a reroute actually takes place allows a smooth transition from one route to another. In a highly loaded network, however, it is possible that sufficient bandwidth cannot be reserved on the new route while the old route is still active – the old route blocks the new route. We consider further investigation of our heuristics considering different deployment scenarios for WMNs as well as differing traffic and heuristic parameter configurations as highly interesting.

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