ROUTING AND PERFORMANCE-AWARE SCHEDULING FOR MULTI-HOP WMN

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ABSTRACT

Routing in multi-hop wireless networks involves the indirection from a persistent name (or ID) to a locator. One of the biggest issues in routing is providing adequate connectivity while scaling the network. IEEE 802.16 employs TDMA (Time Division Multiple Access) as the access method and the policy for selecting scheduled links in a given time slot will definitely impact the system performance. We propose a collision-free centralized scheduling algorithm for IEEE 802.16 based Wireless Mesh Networks (WMN) to provide high-quality wireless multimedia services. We design a relay strategy for the mesh nodes in a transmission tree, taking special considerations on fairness, channel utilization and transmission delay. We evaluated the proposed algorithm with four selection criteria through extensive simulations and the experimental results are instrumental for improving the performance of IEEE 802.16 based WMNs in terms of link scheduling. This work is the first one on the centralized scheduling for IEEE 802.16 mesh mode that considers the relay model.

Keywords: Wireless Mesh Networks, Wireless access networks, IEEE 802.16, Link scheduling.

1 INTRODUCTION

Routing in wireless ad-hoc networks have had to grapple with the twin requirements of connectivity and scalability. While effective in providing high connectivity, as networks grow, however flooding poses an obvious scalability problem. In response, several topology-based routing protocols such as OLSR [6], Hierarchical Routing [7], among others, have implemented limited flooding techniques to disseminate route information. The rapid growth of high-speed multimedia services for residential and small business customers has created an increasing demand for last mile broadband access.

Traditional broadband access is offered through digital subscriber line (xDSL), cable or T1 networks. Each of these techniques has different cost, performance, and deployment trade-offs. While cable and DSL are already being deployed on a large scale, Fix Broadband Wireless Access (FBWA) systems [1,2] are gaining extensive acceptance for wireless multimedia services with several advantages. These include avoiding distance limitations of DSL, rapid deployment, lower maintenance and upgrade costs, and granular investment to match market growth [2]. Study group 802.16 has been formed under IEEE Project 802 to recommend an air interface for FBWA systems that can support multimedia services [3].

Compared with traditional wireless ad hoc networks, wireless mesh networks have the following distinct features [4,5]. First, wireless mesh networks are not isolated self configured networks and emerge as a flexible and low-cost extension of existing wired infrastructure networks. Generally, WMNs serve as access networks that Employ Multihop forwarding to relay traffic. Power consumption is not a primary concern in such an environment because the mesh nodes are fixed and wire-powered. Mostly involved communication is to and from wired gateway (Base Station), rather than between pairs of end-nodes. Moreover, nodes in a mesh network are either stationary or minimally mobile. Thus, contrary to routing in mobile ad hoc networks the links in WMNs have much longer duration times. At last, most applications of WMNs are broadband services with various QoS requirements [4].

In IEEE 802.16 protocol stack, the medium access control layer (MAC) supports both point-to-multipoint (P2MP) mode and mesh (multipoint-to-multipoint) mode. In the mesh mode, scheduling is one of the most important problems that will impact the system performance. A scheduling is a sequence of fixed-length time slots, where each possible transmission is assigned a time slot in such a way that the transmissions assigned to the same time slot do not collide. Generally, there are two kinds of scheduling – broadcast and link. In a broadcast scheduling, the entities scheduled are the nodes themselves. The transmission of a node is intended for, and must be received collision-free by all of its neighbors. While in a link scheduling, the links between nodes are scheduled. The transmission of a node is intended for a particular neighbor, and it is required that there be no collision at this receiver. WMNs have much longer duration times.

2 IEEE 802.16 WIRELESS MESH MODE

In IEEE 802.16 P2MP operation, wireless links operate among a central Base Station (BS) and a set of Subscriber Stations (SSs). The BS is the only transmitter operating in the downlink (from BS to SS), so it transmits without having to coordinate with other stations. Subscriber stations share the uplink to the BS on a demand basis. Whereas in the mesh mode, all nodes are organized in an ad hoc fashion, each node can relay traffic for others and QoS is provisioned on a packet-by-packet basis. A system that has a direct connection to backhaul services outside the mesh network is termed the Mesh BS. All the other systems of a mesh network are termed Mesh SSs. Uplinks and downlinks are defined as the directions to and from the Mesh BS, respectively. Mesh differs from P2MP mode in that in the mesh mode, traffic can be routed through other Mesh SSs and can occur directly between the Mesh SSs, whereas in the P2MP mode, traffic only occurs between the BS and SSs. Moreover, unlike P2MP mode, the mesh mode only supports Time Division Duplex (TDD) for uplink and downlink traffic [3]. For the transmission, several SSs share the wireless channel in a TDMA fashion. In what follows, unless specified otherwise, we will refer to BS and SS as Mesh BS and Mesh SS, respectively. And we will use the terms SS and node interchangeably. A new SS, say u, entering IEEE 802.16 based WMN obeys the following procedures. At first u scans for MSH-NCFG (Mesh Network Configuration) messages to establish coarse synchronization with the network (the cost of synchronization phase is beyond the scope of this paper). Then u shall build a physical neighbor list from the acquired information. From this list, u selects a Sponsoring Node (SN) according to some policy. A sponsoring node is defined as a neighboring node that relays MAC messages to and from the BS for u. Namely, it is an upstream node that is closer the BS. Registration is the process where u is assigned its node ID. After entering the network, a node can also establish links with other nodes. Fig. 1 gives an example of network topology which is composed of one BS and 11 SSs. There is a link between two SSs if they are within the transmission range of each other. Fig. 2 shows the corresponding scheduling tree (or called transmission tree) that only contains the transmission links between a node and its SN. We define the omitted links in Fig. 2 (compared with Fig. 1) as interference links. BS will periodically broadcast MSH-CSCF (Mesh Centralized Scheduling Configuration) messages that include the complete topology of scheduling tree to the nodes. Due to the centralized nature of the scheduling algorithm, there is no hidden terminal problem here. In IEEE 802.16 based WMNs, communications going through all the transmission links shall be controlled by a scheduling algorithm. There are three kinds of scheduling in IEEE 802.16 mesh mode: centralized, coordinated distributed and uncoordinated distributed scheduling. We will brief the general idea of centralized scheduling (the focus of this paper) below. For distributed scheduling, we refer interested readers to [9]. Using centralized scheduling, the BS shall gather traffic demands through MSH-CSCH (Mesh Centralized Scheduling) messages from all the SSs within a certain hop range and communicates the information to all the SSs. Subsequently, the SSs determine their own transmission opportunities in a distributed fashion, using a common predetermined algorithm with the same input information. Therefore, the outputs are the same for all these SSs. The SSs will let the BS know their changes of traffic demands through MSH-CSCH messages. Then the BS will rebroadcast the adjusted traffic demands and the SSs can recalculate their transmission opportunities. To quote IEEE 802.16 standard [9], the advantage of centralized scheduling is that ‘‘it is typically used in a more optimal manner than distributed scheduling for traffic streams, which persist over a duration that is greater than the cycle time to relay the new resource requests and distribute the updated schedule’’. However, the detail of this centralized algorithm is not defined in IEEE 802.16 standard.

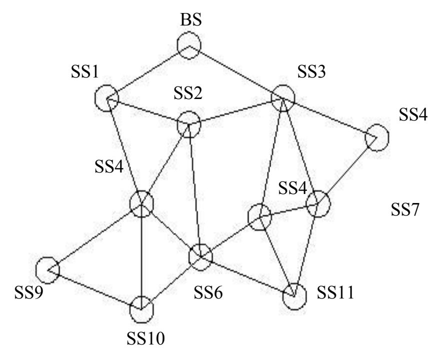

Fig. 1. Network Topology.

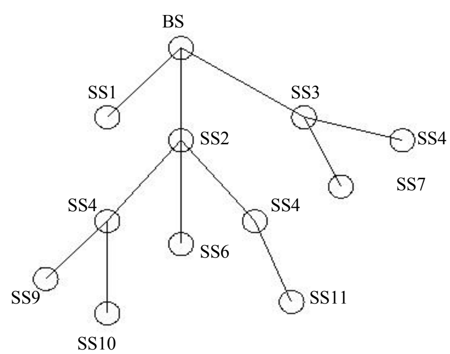

Fig. 2. Scheduling Tree

3 ROUTING PACKETS FROM THE INTERNET TO WIRELESS MESH NODES

In this section, we briefly introduce the three backward path routing protocols that we compare in this paper: AODVCGA, FBR, and GSR. Subsequently, we introduce FBR-GW, an enhancement to FBR that improves its scalability to the network size. Then, we present GSR-PN, an enhanced GSR protocol with higher packet delivery ratio.

3.1 The Protocols under Study

1) AODV-CGA (Reactive Hop-by-hop Routing): As the representative of the class of reactive routing protocols, we use an extended version of AODV that we call AODV-CGA. This extended AODV protocol allows the use of multiplegateways to the Internet and was proposed by Braun et al. [3]. AODV-CGA shares most mechanisms with the well-known AODV protocol and thus may be seen as a benchmark in our comparison. The basic principle of operation of AODV is as follows. AODV constructs routes on demand by flooding route requests using an expanding ring search mechanism. If a request reaches a destination, the destination node answers with a route reply message that is forwarded using temporarily stored information from the request. The reply concurrently establishes the route by registering it at every intermediate node. In AODV, route error messages and sequence numbers are used to deal with broken routes.

As proposed by Braun, all gateways are connected to a dedicated router that acts as a proxy to the Internet. This router has two tasks: (i) on the forward path, it sends route replies on behalf of hosts in the Internet; (ii) on the backward path, it initiates route requests for nodes in the wireless mesh network. To improve scalability with respect to the network size, expanding ring search [10] is used for the route requests, which slightly increases the route set-up time.

2) FBR (Proactive Field-based Routing): As the representative of the proactive routing protocol family, we propose a field-based routing protocol similar to HEAT [4]. In HEAT, wireless mesh nodes periodically exchange beacons. These beacons contain a list of all known destinations with their respective field value. When a new destination appears, it announces its presence with beacons to its neighbors in order to establish a field. With this mechanism, a field on the network is constructed for every destination. This field assigns a value to every node in the network; the destination bears the maximum value. Packets are then routed along the steepest gradient towards the destination. Owing to the fundamental properties of fields, loop freedom of routes is ensured, and it is guaranteed that packets are routed towards the destination [11]. Field-based routing enables nodes to consider multiple routes to the destination, thus if the neighbor with the highest field value disappears, an alternative route can be determined easily if one is available. Note, that FBR—being a proactive routing protocol—incurs a small communication overhead since it proactively maintains all routes, regardless of whether there is data traffic or not.

3) GSR (Gateway Source Routing): With gateway source routing (GSR) [4], we propose to reuse the forward path information from the packets that arrive at the gateways. In the routing header of every packet, the intermediate hops from the mesh node to the gateway are recorded. These paths are then stored in the gateways. To route packets to a mesh node, the mesh gateway inverts the recorded forward path and copies it to the packet header. The gateway then sends the packet to the first node of the backward path. Each node updates the path in the header by removing its entry and forwards the packet to the given next hop until the packet reaches the destination.

By design, this approach is scalable to the number of mesh nodes as it imposes no overhead that depends on this number. Only the gateways have to maintain up-to-date routes to individual mesh nodes. Also, this approach does not increase the number of control packets exchanged between the mesh nodes, and thus reduces the chance of collisions.

Obviously, GSR requires that a packet towards a host in the Internet is first sent by a mesh node in order to establish the backward path. However, since the majority of communication is initiated by mesh nodes, we consider this to be only a small limitation.

Should a mesh node act as a server, a dedicated addressing mechanism (e.g., HIP [12], [13]) would probably be used. HIP and most other addressing mechanisms require periodic registration messages from the mesh node towards a gateway. Those periodic registration messages serve also to initiate and maintain the path at the gateway. Should traffic be unidirectional from an Internet node towards a mesh node, this posesa problem, as the backward path cannot be maintained. This problem can only be solved by requiring the mesh node to periodically send some sort of ping packets to a gateway. Note, however, that most applications have a feedback channel (i.e., TCP acknowledgments or RTCP messages for streaming applications) and hence generate bidirectional traffic. In our evaluation study in Section V, we evaluate a broad range of feedback intervals to shed some light on the trade-off between communication overhead and the quality of the backward path.

3.2 Enhancements

Based on simulation experiments, we propose enhancements to our protocols. With FBR-GW we aim to improve the scalability to the network size of FBR and with GSR-PN we strive to improve the packet delivery ratio of GSR.

1) FBR-GW (Enhancement for Scalability): The FBR protocol is designed for maximum packet delivery ratio, but it scales poorly with the network size. Routing from the mesh nodes to the Internet gateways requires only a single field. In contrast, routing from the gateways back to the mesh nodes requires a separate field is for every mesh node. Thus, a field of every node is propagated through the entire network. Assuming that there are no connections among the mesh nodes, the scalability to the network size can be improved as follows: We propose to let the field information of mesh nodes only be propagated towards the gateways. Implementing this enhancement is straightforward. Instead of establishing the "per-node" field with all neighbors, only the neighbors with an increasing "gateway field" value are used to establish a mesh node field. As a result, state information about individual mesh nodes is only established in nodes that might be used for packet forwarding.

2) SR-PN (Enhancement for Performance): The GSR protocol is designed for scalability to the network size. However, its packet delivery ratio drops rapidly if the routes

are not frequently updated by feedback packets. Most packets are lost due to paths that contain links that are broken because the nodes moved away from each other. Such link breaks happen mostly between nodes that are almost at the maximal transmission range to each other. In order to reduce the probability of mobility-inducedlink breaks, we propose to add a preferred neighbor (PN) mechanism to GSR that is similar to the mechanism we presented in [29]. With this mechanism, links between nodes at a preferable distance are used whenever possible. To this end, nodes are classified into three groups, based on the received signal strength value (RSSI), see Fig. 2:

- *Preferred Neighbor (PN) group:* nodes with a signal level in the preferred range;
- *In group*: nodes with a signal stronger than the preferred level;
- *Out group*: nodes with a signal weaker than the preferred level.

To classify a node, the power of a received signal is compared to two values: Inner Threshold (IT) and Outer Threshold (OT).

4 SCHEDULING SCHEME

4.1 Problem definitions and modeling

As mentioned above, the considered traffic in IEEE802.16 based WMNs is mainly to and from the BS, thus we focus on link scheduling in this paper. In IEEE 802.16 mesh mode, the underlying TDMA communication is structured into frames, each composes of several equal duration time slots. Therefore, in this TDMA based scheduling scheme we make a considerable effort at maximizing the spatial reuse of the available bandwidth while at thesame time eliminating the possibility of collision. We define the closed one-hop neighbor set of node u as Nb[u] (u is also in this set) and the set of nodes sponsored by node v as Sons(v). The cycle of a link scheduling is the time needed to transmit all the traffic to/from the BS in the WMN, under certain traffic model. The length of a link scheduling is the number of time slots in the cycle. The cycle keeps repeating until the next scheduling update. The channel utilization ratio (CUR) is defined as the ratio between the number of occupied time slots and the total number of available time slots (the length of scheduling multiplied by the number of nodes). Note that, the resulted CUR is, in fact, the average CUR for all SSs. The average transmission delay is the number of time slots between the time slot when a packet is transmitted by the source SS and the time slot when the same packet arrives at the destination. Suppose a packet is sent out in time slot 2 and arrives to the destination in time slot 7, the transmission delay is then calculated as 5 time slots. Here, we consider the following special scheduling problem: how to assign time slots to transmission links in IEEE 802.16 based WMNs so as (1) to reduce the length of scheduling; (2) to improve the channel utilization ratio and (3) to decrease the transmission delay, subjected to some constraints presented below.

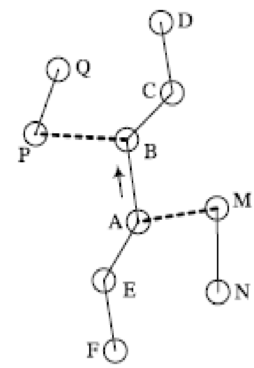

Fig. 3. Interference model

In particular, depending on the signaling mechanism ,transmissions may collide in two ways in wireless networks: primary and secondary interference [8]. Primary interference occurs when a node has to do more than one thing in a single time slot. The reason for this constraint is that the nodes cannot transmit and receive simultaneously and cannot transmit/receive more than one packet at the same time. Thus, this constraint is also referred to as the transmission/ reception constraint. Secondary interference occurs when a receiver R tuned to a particular transmitter T is within the range of another transmitter whose transmissions, though not intended for R, interfere with the transmissions of T. This constraint is also referred to as the interference-free constraint. We do not explicitly consider non-collision-related channel errors in this paper. We can use the partial topology in Fig. 3 to illustrate the interference model more clearly. In this figure, two nodes that are within the transmission range of each other are connected by a link. The solid lines represent the transmission links in the scheduling tree and the dashed lines represent the interference links. We stress that although there is no traffic transmitted over interference links and these links do not have to be scheduled, they may induce conflicts between transmission links. Suppose the node in the higher part of the figure is closer to the BS and the link from node A to B (uplink) is scheduled in the current time slot. Due to these two kinds of interference, nodes B, C, E, F, N and P cannot transmit through their uplinks in the same time slot. In fact, these interfered nodes can be divided into two groups: (1) Nb[B]–{A}, such as nodes B, C and P and (2) Sons(Nb[A]–{B}), such as nodes E, F and N. For example, if node P is scheduled to transmit to Q, B will receive packets from both A and P. If node N is scheduled to transmit to M, M will receive packets from both A and N. Thus, these transmissions will collide. Note that, in IEEE 802.16 mesh mode, uplinks and downlinks are scheduled separately. In this paper we only describe the scheduling algorithm for uplinks and it can be easily extended to the case of downlinks.

4.2 Transmission-tree scheduling (TTS) algorithm

In the proposed algorithm, a SS is assigned service token based on its traffic demand. We use service token to allocate time slots to each link proportionally according to the traffic demand of the link's transmitter, thus, the fairness is guaranteed (no nodes will be starved). A link can be scheduled only if the service token number of its transmit is nonzero.

Each time after a link is assigned a time slot, the service token of the transmitter is decreased by one and that of the receiver is increased by one. Thus, using the change of service token, we can easily integrate the hop-by-hop relay model of WMN into our algorithm. Suppose there are totally n SSs and the traffic demand of SS_i is tr_i. Then the service token assigned to SS_i will be $token_i = tr_i/g$, where g is the greatest common divisor (GCD) of $tr_1, tr_2, \ldots tr_n$. We divide the traffic demands by their GCD to reduce the length of scheduling. For example, if the traffic demands of the SSs are 2Mbps, 8Mbps, 6Mbps and 4Mbps. The service tokens assigned to the SSs will be 1, 4, 3 and 2. Compared with the service token assignment 2, 8, 6 and 4, the length of resulted scheduling is reduced to half. Here, we name the set $\{token_i\}$ as ST. Fig. 4 gives the details of the algorithm. Suppose the length of the resulted scheduling is k. The inputs of this algorithm are the scheduling tree T and the service token set ST, and the output is an $n \cdot k$ scheduling matrix S. If node i is scheduled in time slot j, $S_{ij} = 1$, otherwise, $S_{ij} = 0$. Initially, all the elements in S are 0. In each round (for the while loop), initially, if the service token of the transmitter of a link is nonzero, this link is marked as available, otherwise, it is marked as idle. An available link satisfied with some selection criterion (to be discussed later) is scheduled in the current time slot. The selected link is marked as scheduled and all the conflicting neighboring links of it are marked as interfered. The service tokens of the transmitter and receiver of this scheduled link are also adjusted. Then, the next scheduled link is selected based on the same rule. The selection is repeated until none of the links are marked as available. The same procedure is repeated until the service tokens of all these SSs are decreased to 0. The implementation of function select_one_link() is

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Algorithm TTS
Input: Scheduling tree T = (V, E) and service token set ST
Output: A time slot assignment S
k = 1;
assign service token to each SS
while ∃token_i ≠ 0 do
   mark the status of all transmission links in E (available or idle)
   while ∃e∈E and status (e) = available do
      m = select_one_link();
      status (m) = scheduled;
      adjust_service_token (m);
      S_mk = 1;
      mark_interference (m);
   end while
   k++;
end while
```

determined by different selection criteria. In this paper, we consider four kinds of criteria: random, min interference, nearest to BS (hop count) and farthest to BS. In random selection, each time the scheduled link is selected randomly In the min interference selection, the link whose transmitter interferes the minimal number of other SSs is chosen for scheduling. While in the nearest to BS and farthest to BS selections, the link whose transmitter has the minimal or maximal hop count to the BS is scheduled. If two SSs have the same number of interfered neighbors or the same hop count to the BS, we use the node ID to break the tie and choose the SS with the smaller node ID. Note that, when the service token of nodes with smaller ID is decreased to 0, nodes with higher ID will get the chance to be scheduled, thus will not be starved forever. Moreover, the transmission slots assigned to a node is determined by the number of its server tokens. Therefore, when tie occurs, nodes with smaller ID cannot always transmit more frequently than nodes with higher ID.

4.3 Buffer management policy

One major difference between our proposed algorithm and the existing approaches is that we integrate the inherent relay model of access networks into this scheduling algorithm. Each node will take care of both its own data and the data forwarded for its children if there is any. Because a node can only transmit one packet when it gets a transmission opportunity, data packets from its children may be buffered into a queue. The emphasis of this paper is the link scheduling algorithm in IEEE 802.16 mesh mode. Thus, for simplicity, first in, first out (FIFO) is used to manage the buffer in the following simulation study. That is, we distinguish the data packets arriving at a given node according to their arrival time. Evaluating the impact of other queueing models, such as Earliest Deadline First with Frame Reservation (EDF-FR) and Start Time Fair Queueing (STFQ) is our current research work.

5 CONCLUSION

Wireless mesh networks are a large-scale solution to provide Internet access to mobile users. In such a network, mesh gateways provide Internet access to nodes in their vicinity; data from and to mesh nodes further away is relayed through the mesh network. Routing data to the gateways is fundamentally different from routing towards specific mesh nodes.

We proposed a collision-free centralized scheduling algorithm for IEEE 802.16 based WMNs. In this algorithm,we consider some particular features of WMNs,such as the function of access networks. The inherent relay model is also integrated into this scheduling algorithm.This scheduling scheme takes fairness, channel utilization and transmission delay into consideration. In the proposed algorithm, the selection policy for scheduled links will impact the algorithm's performance. We use the length of scheduling, channel utilization ratio and transmission delay to evaluate the performance of the proposed scheduling algorithm.

Our current work includes investigating the impact of different buffer management policies on the transmission delay and further research on the computation complexity of the proposed scheduling problem. Moreover, we are considering using some advanced techniques, such as directional antenna and multi-channel/multi-radio to improve the channel utilization.

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