End-to-End Delay Assurances in Multihop Wireless Local Area Networks

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***Abstract*— In this paper, we address the problem of providing multiple classes of delay assurances to end-to-end applications in a multihop wireless local area network (WLAN) architecture. Specifically, mobile users form multihop wireless connections towards an access point (AP) for Internet access. In this context, not all users are directly reachable by AP. Users are potentially distributed in an area larger than one common contention medium and are subject to physical channel variations and mobility induced topology changes, all of which contribute to large variation in end-to-end packet delays. The paper formulates the delay assurance problem in multihop WLAN and proposes a solution framework together with an approximate implementation. Finally, with simulation, it demonstrates the substantially enhanced delay assurance provided with the framework as compared to the 802.11 baseline service over stationary and mobile multihop WLAN scenarios.**

I. Introduction

Wireless local area networks (WLAN's) based on the IEEE 802.11 standards [9], [11] are increasingly being deployed to provide the "hot-spot" access to the global information infrastructure. In these networks, a base station (or access point, AP) acts as a gateway between mobile users[1] and the wired network. While most IEEE 802.11b based networks assume direct (single-hop) communication between a mobile node and an AP, the situation is expected to change in the near future. This is because the emerging IEEE 802.11a standard [10] typically supports higher data rates (up to 54 Mbps) only over short distances (approximately 100 ft). For mobile nodes to achieve the higher data rates from larger distances, nodes must operate in a multihop mode in which a node forwards messages for other nodes. This paper addresses some of the key challenges in concurrently providing a wide range of end-to-end delay assurances in multihop WLAN's.

Numerous delay assurance mechanisms have been proposed for WLAN. Centralized solutions [20], [26] utilize the Point Coordination Function (PCF) of IEEE 802.11 to schedule all delay constrained flows for delivery in Contention Free Periods. PCF solutions are applicable only if all users are directly reachable from the AP and are closely synchronized. Substantial overhead is its downside [16]. Distributed solutions are based on the Distributed Coordination Function (DCF) of IEEE 802.11. DCF uses carrier sense multiple access with carrier avoidance to coordinate user access to the medium. Distributed delay assurance solutions moderate the contention behavior of DCF in its carrier sensing [19], inter-frame spacing (IFS) [1], [2], [18], and contention window (CW) adaptation [1], [2], [15], [18], [23] to provide differentiated delays. The consolidation of several such service differentiation techniques lead to the supplement standard 802.11e. Though not yet standardized, it is expected to provide multiple classes of prioritized medium access. It has been evaluated in several recent studies [4], [8], [16].

Due to incomplete carrier sensing, DCF often results in unfair medium access in multihop wireless networks [25]. There are distributed fair queueing methods that facilitate controlled bandwidth sharing among single-hop flows in the same contention medium [7], [17], [22], [14]. The bandwidth sharing is defined by weights that must be determined among all competing flows. Resource reservation with a centralized knowledge of all competing flows is necessary. The complexity of resource reservation is more acute for multihop flows extending beyond a single contending area. Topology changes due to mobility further complicate the reservation task. *In this paper, we propose a fully distributed service framework to provide end-to-end delay assurances for multihop flows in such networks.*

The proposed delay assurance framework is based on the Proportional Delay Differentiation (PDD) network service model [6]. The PDD model supports a certain number of service classes *relatively ordered* in terms of queueing delays. In this model, an application chooses a service class for each of its packets [5] and each node handles an incoming packet based only on its class. The class queueing delays are proportional to a set of chosen *class differentiation parameters* and this proportionality is expected to hold at each node independent of the aggregate arrival and its class distribu-

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[1] In this paper, the terms *user* and *node* are used interchangeably and are clear to the context.

tion. This consistency in differentiation alleviates two major challenges in a multihop WLAN. First, due to its medium access properties, the achievable bandwidth by each node is dependent on the total number of contending nodes, their respective traffic arrivals, and moreover, each node's access priority if there are more than one. With such a dynamic bandwidth resource, delay assurances through mechanisms in Integrated Services (IntServ) [24] and Differentiated Services (DiffServ) [3] (Expedited Forwarding, EF, [12] specifically) are difficult to realize. Second, as end-to-end routes change in a multihop WLAN, traffic aggregation changes on each node. For IntServ, it means resource reservation must be redone; for EF, excessive traffic aggregation potentially fails the assurance. If the proportionality in the PDD model holds independent of the available bandwidth and traffic arrival distribution, then these issues are resolved.

The PDD model in [6] was proposed for wireline networks. In a wireline network, contention occurs only among packets sharing a link. As a result, proportionality is only required to hold *locally* at each node. In contrast, in a multihop wireless network, packets at all nodes are potentially contending with each other. There comes the question whether the proportionality should hold locally at each node or globally across all nodes. If it should hold only locally, no coordination is required among nodes. However, as stated earlier, unfairness in medium access among nodes can adversely affect the absolute delays at a node. This problem does not arise if it holds globally across all nodes. In this case, medium access must be coordinated among nodes to satisfy the global requirement. However, fairness in accessing the medium is assured. In this paper, we chose the latter approach. We extend the PDD model from [6] to provide consistent global PDD among nodes contending for the same medium. We refer to the extended model as *Neighborhood Proportional Delay Differentiation* (NPDD). The NPDD is realized with a work-conserving proportional scheduler and a collaborative medium access priority selection (MAPS) mechanism. For users to choose the right class meeting their delay bounds, a Dynamic Class Selection algorithm [5] is adopted to select the lowest (presumably cheapest) satisfactory class.

The rest of this paper is organized as follows. Section II formulates the end-to-end delay assurances problem in a contention based multihop WLAN. Section III describes the proposed framework with its critical component techniques. Simulation studies of multiple classes of delay sensitive flows over stationary and mobile multihop WLAN's are presented in Section IV. Section V concludes the paper.

II. Problem Statement

We consider a multihop WLAN with an AP being the Internet gateway of all mobile users. Any user can host applications with remote connection requests while all connections must go through the AP. To simplify our model, all connections start or end at the AP. Thus, all users form connections of one or multiple hops towards AP with the underlying routing protocol. The medium access for each node assumes IEEE 802.11 DCF with RTS/CTS and the IEEE 802.11e differentiation extension. Not all users or AP are within each other's transmission and carrier sensing range. In this network, the multiple classes end-to-end delay assurance problem is formulated as follows:

An application f at a node k requests that all its packets have a bound on their end-to-end delays. The network strives to meet this bound but does not guarantee it. We use the percentage of packets delivered within the desired bound as a measure of effectiveness of the proposed scheme.

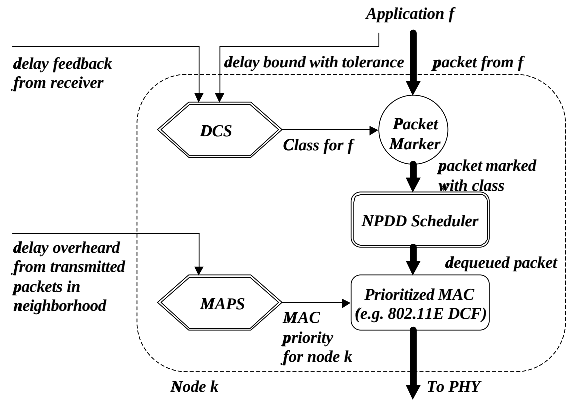

Fig. 1. DCS-NPDD-MAPS framework for end-to-end delay assurance over a multihop WLAN.

III. Proposed Solution: The DCS–NPDD–MAPS Framework

A. Overview

Figure 1 illustrates the proposed DCS-NPDD-MAPS framework. Here we describe its ideal methodology while implementation issues are presented in the following section. While in our problem an application specifies an arbitrary end-to-end delay bound, the NPDD service provides a finite number of delay differentiation classes. DCS selects the NPDD service class for an application such that the delay bound is met. As elaborated later, the NPDD service provides consistent *global* proportional delay differentiation within the same contending set. Such a differentiation requires adaptive bandwidth adjustment at each node with the underlying prioritized MAC layer, such as the 802.11e DCF. MAPS monitors the average NPDD delays and selects the MAC priority such that NPDD holds.

The NPDD service supports N classes relatively ordered in per-hop packet queueing delays at any node k. At node k, packets from class i experience smaller delays than class j for all $i < j$, $i, j \in S_B$ where S_B is the set of backlogged classes. The spacing between the delays is tuned by the network designer with a set of class differentiation parameters. Here we define two nodes k and q to be in the same contending set if there exists a route between them. NPDD for a multihop WLAN is described as follows.

Let $1 = \delta_1 > \delta_2 > \cdots > \delta_N > 0$ *be* $N - 1$ *independent* *delay differentiation parameters (DDP's) provisioned by the network designer. Let $\bar{d}_i^{(k)}$ denote the average queueing delay of class i packets at node k. The queueing delay is defined as the difference between the time a packet arrives at the node and the time the packet is transmitted again. The NPDD requirement is*

$$\frac{\bar{d}_i^{(k)}}{\bar{d}_j^{(q)}} = \frac{\delta_i}{\delta_j}, \tag{1}$$

for all classes i and j and for all pairs of nodes k and q such that k and q belong to the same contending set. Define the normalized average queueing delay $\hat{d}_i^{(k)}$ for class i at node k as

$$\hat{d}_i^{(k)} = \frac{\bar{d}_i^{(k)}}{\delta_i}. \tag{2}$$

If NPDD holds, all backlogged classes at all contending nodes have the same normalized average queueing delay. That is,

$$\hat{d}_i^{(k)} = \hat{d}_j^{(q)} \quad \forall i, j \in \{1...N\} \tag{3}$$

for any two nodes k, q in the same contending set.

Note that, if NPDD holds, packets traversing through lightly loaded portions of a network will experience delays comparable to those traversing heavily loaded regions. From one perspective, this can be viewed as undesirable because it implies that all nodes do not get the same share of the bandwidth. On the other hand, we contend that providing a consistent delay across all nodes is more desirable than consistent share of bandwidth, especially in a mobile multihop network with considerable traffic and topology dynamism.

B. Implementation

1) Dynamic Class Selection (DCS): Application f's end-to-end delay $D_f(m)$ along route $R_f(t)$ equals the sum of per-hop delays at all nodes $k \in R_f(t)$. When NPDD holds at node k, the average per-hop delay $\bar{d}_i^{(k)}$ for class i is ordered as $\bar{d}_i^{(k)} \leq \bar{d}_j^{(k)} \forall i > j$. This implies that along a specific end-to-end route, packets of a higher class have shorter end-to-end delays than those of a lower class. As a result, we adopt the DCS mechanism in [5]. An application f specifies its delay bound $\hat{D}_f$ with a tolerance δD_f. DCS starts with a lowest initial class. Based on delay feedbacks, if f's has an average delay $\bar{D}_f > \hat{D}_f$, the class increases by 1. If delay drops and $\bar{D}_f < \hat{D}_f - \delta D_f$, the class decreases by 1. At convergence, DCS either assigns a class that meets f's delay bound, or the highest available class if $\hat{D}_f$ cannot be met. Implementation details follows [5].

2) NPDD Scheduler: The ideal model described in Section III-A is difficult to realize. Here we propose an implementation consisting of an NPDD Scheduler and the MAPS mechanism that approximate the model to a certain extent. The scheduler supports N classes using the Waiting Time Priority (WTP) algorithm [6]. Each class is serviced with a separate First-In-First-Out (FIFO) queue. The head packet of each class is assigned a *waiting time priority* $\tilde{w}_i(t) = w_i(t)/\delta_i$ where $w_i(t)$ is the time the class i head packet has waited in the queue. The scheduler always dispatches the highest priority head packet for service. To facilitate MAPS, each dispatched packet is marked with its priority $\tilde{w}_i(t)$ and the node's estimate of its contending set's *average normalized delay* $\bar{d}_{S,k}$ (maintained by MAPS).

3) Medium Access Priority Selection (MAPS): Given P levels of MAC priorities, MAPS performs two tasks: (i) to maintain an *estimate* of the node's average normalized delay $\bar{d}_{N,k}$ and its contending set's *set normalized delay* $\bar{d}_{S,k}(t)$ by overhearing delay information in packets transmitted in its neighborhood, and (ii) to decide the MAC priority whenever the node transmits a packet.

The waiting time priority $\tilde{w}(t)$ is essentially the *normalized queueing delay* of a packet analogous to Equation 2. Thus, a node's $\bar{d}_{N,k}$ is defined as the moving average of $\tilde{w}(t)$'s of all its previously serviced packets. $\bar{d}_{S,k}(t)$, on the other hand, is updated by overhearing packets from any node q in its neighborhood as a linear combination of the current $\bar{d}_{S,k}(t)$ and $\tilde{w}_i(t)$, $\bar{d}_{S,q}$ carried with the packet. Hence, $\bar{d}_{S,k}(t) = \gamma\tilde{w}(t) + \kappa\bar{d}_{S,q}(t) + (1 - \gamma - \kappa)\bar{d}_{S,k}(t)$, where γ and κ are weighting parameters. With $\bar{d}_{N,k}(t)$ and $\bar{d}_{S,k}(t)$, MAPS computes an index $I_k(t) = \frac{\bar{d}_{N,k}(t)}{\bar{d}_{S,k}(t)}$ for priority assignment. P parameters are defined as there are P priorities, $0 < \epsilon_1 < \epsilon_2 < ... < \epsilon_P = \infty$. MAPS assigns priority r at time t if and only if $\epsilon_{r-1} \leq I_k(t) < \epsilon_r$, where $\epsilon_0 = 0$.

IV. Simulation Studies

Simulation studies of the DCS-NPDD-MAPS framework are conducted using the network simulator *ns-2* [21] with its *CMU mobilenode extension*. The topology models a multihop WLAN with 30 users arranged in two circles. The AP is at the center with 10 *In-Range users* within its direct transmission range and the remaining 20 *Out-of-Range users* beyond that range. All users reach AP with multihop paths discovered with Dynamic Source Route (DSR) [13]. Routes are not necessarily shortest paths and are at times more than two hops.

Table I lists the chosen parameters for individual components in the service framework. The *baseline* service features a single FIFO scheduler over base 802.11 with no priorities, the *DCS-NPDD* service provides class based NPDD differentiation over base 802.11, and finally the DCS-NPDD-MAPS implements the full solution with both network and medium access differentiation. In all experiments to be presented, the same set of traffic arrival is applied to each user: two uplink UDP streams towards AP with (I) exponentially distributed *ON* and *OFF* intervals of the same mean $128ms$, (II) the same packet size 512 bytes, (III) and the same *ON period* mean arrival rate 161 kbps. There are totally 60 flows emanating from the 30 users. All experiments last for 200 seconds.

A. Baseline Service Delay Distribution

The baseline service provides *best effort* service to all flows without differentiation. The first experiment applies the designed arrival to the *baseline* network and simply observes

Scheme	*DCS-NPDD-MAPS*	*DCS-NPDD*	*Baseline*
DCS tolerance $\Delta(x)$, x: delay bound	$0.5x$	$0.5x$	∞
DCS delay moving average weight w	1	1	*N/A*
NPDD classes	4	4	1
DDP δ_i, $i \in 1, 2, 3, 4$	$[1\ \frac{1}{2}\ \frac{1}{4}\ \frac{1}{8}]$	$[1\ \frac{1}{2}\ \frac{1}{4}\ \frac{1}{8}]$	1
Per-class maximum queue size (packets)	600	600	2400
MAPS priorities	3	1	1
MAPS $CWmin_i$, $i \in 1, 2, 3$	[217 124 31]	217	217
MAPS $CWmax_i$, $i \in 1, 2, 3$	1023	1023	1023
MAPS ϵ_i, $i \in 1, 2, 3$	$[2\ 5\ \infty]$	$[\infty\ \infty\ \infty]$	$[\infty\ \infty\ \infty]$
MAPS $d_{G,k}$ average weight (γ, κ)	(0.1, 0.1)	*N/A*	*N/A*
MAPS $\bar{d}_{N,k}$ moving average weight σ	0.9	*N/A*	*N/A*
802.11 modes	802.11e/802.11a	802.11a	802.11a

TABLE I

PARAMETERS OF EVALUATED SERVICE SCHEMES.

the end-to-end delay distribution of all flows. Not shown due to space limit, the delay distribution shows the same dynamic range for flows regardless their originating nodes being In-Range or Out-of-Range.

We denote the upper bound of the delay distribution as d_{max}. The baseline network can only satisfy assurance requests with delay bounds higher than d_{max}. Flows requesting for bounds tighter than d_{max} are unavoidably failed. One question arises: can we do better if some flows have loose bounds much higher that d_{max}, and at the same time other flows request for tighter bounds below d_{max}? The next experiment answers the question.

B. Multiple Delay Assurances

This section presents assurances provided to seven types of applications with delay objectives of 1, 2, 3, 4, 5, 7, and 8 seconds. Table II shows the satisfaction level for each application type over the simulation period. We define the delivery ratio as the percentage of packets successfully reaching their receivers and the in-time ratio as the percentage of packets delivered within their bounds. Dropped packets are considered out-of-bound. Three sub-columns under each metric present the results for the baseline service, the DCS-NPDD service, and the DCS-NPDD-MAPS service. Note that the baseline service provides a single class (class 1) while the other two provide multiple classes. The baseline performance drops significantly for flows with bounds less than $d_{max} \approx 3s$. The baseline delivers only 40% of $1s$-bounded packets and 52% $2s$-bounded packets, while DCS-NPDD and DCS-NPDD-MAPS do not see as sharp a degradation below $3s$. Even so, performance loss is still seen with DCS-NPDD even in loosely bounded flows. Although DCS-NPDD locally differentiates diversely bounded flows with different NPDD classes at each node, it is not always able to acquire sufficient bandwidth at more heavily loaded nodes. At such nodes, the enhanced performance for tight flows is at the cost of originally satisfied flows since the accessible bandwidth remains the same. DCS-NPDD-MAPS resolves the problem by properly allocating more bandwidth to nodes as needed and shows overall the highest level of satisfaction.

C. Delay Assurance for Mobile Users

User mobility leads to network topology changes and thereby route changes. When routes change, traffic aggregation changes significantly at affected nodes. Per-hop packet delay is a function of the aggregate load and bandwidth to each node. Without proper re-allocation of bandwidth, the baseline and the DCS-NPDD schemes can not properly service the rerouted traffic and result in packet losses and excessive delays. As DCS-NPDD-MAPS approximates global PDD (Equation 3), packets of the same class are expected to see same or similar average delays at neighboring nodes. Partial route changes are not expected to cause significant end-to-end delay variations. Even if deviation does occur, DCS adapts the service class to regain assurance. Table III presents the results obtained with the same traffic over a mobile topology. At $30s$, 10 inner nodes start circulating clockwise at 5 m/s. The baseline service lost significantly more packets than the other schemes (see delivery ratios). The baseline also suffers significant loss in in-time ratios, even for loosely bounded flows (39% for $3s$-bounded flows). The delay traces, not shown due to page limit, reflect substantially increased queueing delays (tens of seconds) at certain nodes as a result of traffic aggregation after route changes with the baseline scheme. DCS-NPDD show consistently higher delivery ratio than the baseline, though its in-time ratio remains low. MAPS is critical in reallocating the bandwidth in response to traffic aggregation changes. DCS-NPDD-MAPS incurs the least packet loss and provides consistently more satisfactory delay assurances to all types of flows.

V. CONCLUSION

This paper addresses the challenges of providing end-to-end delay assurances for delay sensitive applications in a multihop WLAN. Now widely deployed WLAN "hot-spots" mostly provide best effort service without delay assurances, while existing assurance mechanisms either provide limited classes of service, or require resource reservation and do not adapt well to multihop flows in a multihop network with traffic and topology dynamism. The paper formulates the end-to-end delay assurance problem over a multihop WLAN with prioritized medium access support. A fully distributed service framework based on proportional delay differentiation and medium access priority selection is proposed. With simulation, we demonstrate the substantially enhanced delay assurance provided with the framework as compared to the 802.11 baseline service over stationary as well as mobile multihop WLAN scenarios.

Scheme	Baseline — *DCS-NPDD* — **DCS-NPDD-MAPS**								
Bound	Delivery Ratio			In-time Ratio			Mean Class		
$1s$	95.1	*97.7*	**100.0**	40.3	*65.2*	**98.5**	1.0	*2.6*	**2.4**
$2s$	94.0	*98.0*	**100.0**	52.2	*82.7*	**97.2**	1.0	*1.7*	**1.8**
$3s$	91.1	*96.2*	**97.1**	91.1	*75.9*	**96.3**	1.0	*2.3*	**1.2**
$4s$	94.3	*96.3*	**95.9**	94.3	*87.6*	**95.5**	1.0	*1.9*	**1.0**
$5s$	92.2	*96.3*	**97.2**	92.2	*89.4*	**97.2**	1.0	*1.6*	**1.0**
$7s$	95.5	*91.9*	**96.3**	95.5	*77.8*	**96.3**	1.0	*1.7*	**1.0**
$8s$	93.4	*91.0*	**96.6**	93.4	*77.4*	**96.6**	1.0	*1.4*	**1.0**

TABLE II

COMPARISON OF BASELINE, DCS-NPDD, AND DCS-NPDD-MAPS SCHEMES IN A STATIONARY MULTIHOP WLAN.

Scheme	Baseline — *DCS-NPDD* — **DCS-NPDD-MAPS**								
Bound	Delivery Ratio			In-time Ratio			Mean Class		
$1s$	50.6	*87.8*	**92.9**	38.1	*62.8*	**82.0**	1.0	*2.4*	**2.2**
$2s$	70.0	*81.1*	**88.2**	66.2	*56.6*	**79.5**	1.0	*2.6*	**1.8**
$3s$	40.4	*77.0*	**82.7**	39.2	*60.0*	**69.7**	1.0	*2.0*	**1.9**
$4s$	70.3	*78.9*	**78.8**	69.2	*66.2*	**73.0**	1.0	*1.7*	**1.4**
$5s$	60.0	*66.4*	**85.2**	58.4	*56.0*	**78.2**	1.0	*1.6*	**1.3**
$7s$	52.3	*72.6*	**79.9**	50.2	*68.5*	**74.8**	1.0	*1.4*	**1.4**
$8s$	62.4	*67.1*	**80.0**	61.0	*64.1*	**76.5**	1.0	*1.2*	**1.1**

TABLE III

COMPARISON OF BASELINE, DCS-NPDD, AND DCS-NPDD-MAPS SCHEMES IN A MULTIHOP WLAN WITH NODE MOBILITY.

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