End-to-end Throughput and Delay Assurances in Multihop Wireless Hotspots

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Abstract

Next generation Wireless Local Area Networks (WLAN's) are likely to require multihop wireless connections between mobile nodes and Internet gateways to achieve high data rates from larger distances. The paper addresses the challenges in concurrently providing end-to-end throughput and delay assurances in such mobile multihop WLAN hotspots. The proposed solution is based on the Neighborhood Proportional Delay Differentiation (NPDD) service model. Transmission Control Protocol (TCP) based applications use a dynamic class selection scheme to achieve desired throughputs. This approach integrates well with the NPDD based end-to-end delay assurance mechanisms proposed earlier. The effectiveness of the proposed solution in meeting desired throughputs is assessed with simulations. The simulation results show that the proposed solution is better in meeting the desired throughputs and delays as compared to two conventional approaches.

I. Introduction

The use of wireless Internet gateways to provide access at hotspot locations such as airports and coffee shops have become commonplace in recent years. Most of these networks today are based on IEEE 802.11 standards [5], [7]. In these networks, the gateway is called as an access point (AP). Two modes of connection are defined: access point mode and ad hoc mode. Most IEEE 802.11b based hotspots now are in access point mode, assuming direct communication between mobile nodes and AP. The situation, however, is expected to change in the near future. The emerging IEEE 802.11a standard supports high data rates up to 54 Mbps but only over short distances (below 100 ft). For mobile nodes to achieve the higher rates, they must operate in ad hoc mode where nearby neighbors forward messages for each other. As a result, we expect future hotspot architectures to be *multihop*, as illustrated in Figure 1. In this paper, we address the key challenges in concurrently providing a wide range of end-to-end throughput and delay assurances in an IEEE 802.11 based multihop WLAN hotspot.

These challenges stem from the following two characteristics expected of a hotspot WLAN:

- Node mobility.
  In public hotspots, nodes may enter or leave the network at any time. They may also wander in the network while actively communicating. Consequently, the number of nodes, the network topology, and the amount of network traffic is always changing.
- Decentralized access to a shared medium.
  In multihop hotspots, nodes are not required to stay within AP's physical transmission range. As a result, it is not feasible to centrally schedule medium access of the nodes. In IEEE 802.11, a decentralized medium access protocol called distributed coordination function (DCF) is used by each node to gain access to the shared wireless medium.

The dynamics due to node mobility and decentralized access often cause unacceptable variations in the quality of service (QoS) perceived by ongoing end-to-end communication in these networks.

Several end-to-end QoS assurance techniques exist in the literature [10], [11], [13], [18]. The existing techniques, can be broadly grouped into two camps, Integrated Services (IntServ) based and Differentiated Services (DiffServ)

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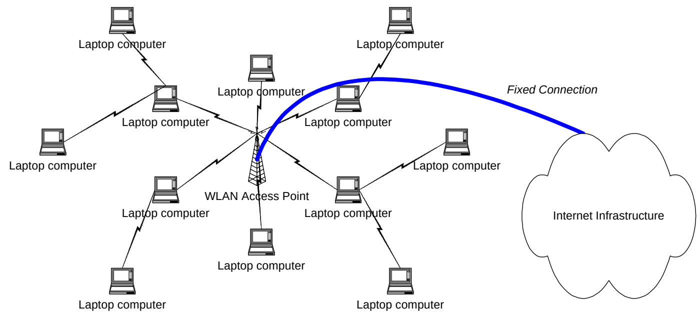


Fig. 1. A multihop WLAN hotspot.

based. IntServ based mechanisms aim to provide each flow with assured QoS along its *specific route* with *per-flow* resource reservation on each node along that route. DiffServ mechanisms, on the other hand, do not perform resource reservation and per-flow operations. A number of service classes are provisioned with certain resources to provide different levels of QoS assurances and applications choose to be serviced in any of these classes. DiffServ mechanisms for QoS assurances at a node are defined as Per Hop Behaviors (PHB's), e.g. the Expedited Forwarding (EF) PHB [8] and the Assured Forwarding (AF) PHB [4]. End-to-end QoS assurances are defined as Per Domain Behaviors (PDB's) based on respective underlying PHB's [13]. The existing IntServ and DiffServ proposals are difficult to implement in a multihop WLAN hotspot. The IntServ based solutions are difficult because resource reservation requires global coordination since the wireless medium is shared by all nodes. Furthermore, available bandwidth varies at each node and as routes change, resource reservation must be redone. DiffServ's EF aims to provide per-hop low delay and it faces similar difficulties in resource provisioning due to the network dynamics. AF provides per-hop throughput assurances through packet marking and selective queue management. Unlike EF, AF does not request for explicit resource provisioning. It assures packets marked with high priorities be serviced before others and throughput assurance is thus achieved by controlling the marking rates. AF alone, however, does not address end-to-end throughput assurances and to our knowledge, there is no efficient PDB solutions based on AF in effect today.

In [17], we proposed a DiffServ based scheme called Neighborhood Proportional Delay Differentiation (NPDD) for multihop WLAN's. In the NPDD model, the network supports multiple service classes. The PHB at each node is such that the ratio of average packet delays in two different classes are equal to a prespecified ratio selected by the network service provider. The PHB requirement must hold independent of each node's dynamic bandwidth and traffic arrival. Based on the NPDD model, [17] addresses the problem of end-to-end delay assurances in such networks. It is shown that an application can effectively choose a class for each packet to achieve its average end-to-end delay requirement even in highly mobile multihop WLAN scenarios. In this paper, we address the problem of assuring end-to-end throughput for Transmission Control Protocol (TCP) based applications using the NPDD service model. The throughput assurance scheme integrates well with the delay assurance approach proposed in [17]. Thus, collectively they provide an effective QoS (end-to-end delay and throughput) differentiation and assurance framework in multihop WLAN's.

The effectiveness of the proposed mechanisms is demonstrated through simulations. Public multihop WLAN hotspots service nodes in random arrivals for random periods of stay. Typical scenarios are hotspots servicing customers in coffee shops or travelers in airports. Existing random mobility models either address channel occupation times and hand-offs in the context of cellular networks [3], [12], or random motion of a fixed population of nodes in ad hoc networks [9]. A multihop WLAN hotspot features random node participation, while nodes potentially move in short distances during their stay. Such mobility is not addressed with the existing models. The Public Hotspot Mobility (PHM) model is proposed. As shown in the paper, the model captures individual node mobility as in coffee shops hotspots and group mobility as in airport hotspots.

The remainder of the paper is organized as follows. Section II briefly reviews IEEE 802.11 medium access control (MAC) and IEEE 802.11e [15], its proposed extension for QoS differentiation. The significance of prioritized medium access in the proposed assurance mechanism is stated. Section III describes the network model, the NPDD service model, and the end-to-end throughput assurance problem. Section IV describes the proposed throughput assurance mechanism. In Section V, we evaluate the proposed scheme with simulation of multihop IEEE 802.11

hotspots with stationary and mobile nodes with the Public Hotspot Model. Finally, Section VI concludes the paper.

II. IEEE 802.11 and IEEE 802.11e

IEEE 802.11 DCF provides an asynchronous carrier sense multiple access scheme with collision avoidance (CSMA/CA) at each node [5]. When a node i wishes to transmit a packet, it chooses a backoff interval of B_i slots. B_i is randomly chosen with uniform distribution in the interval [0, CW_i], where CW_i is the *contention window* of node i. CW_i is reset to CW_{min}, which is a DCF parameter, at the beginning of time as well as after each successful transmission from node i. For every slot the medium is sensed idle, B_i is decremented by 1. Whenever the medium is busy, B_i is frozen until the medium becomes idle again. When B_i reaches 0, node i transmits a Request-To-Send (RTS) packet toward the intended receiver with the intended data transmission length. The destination sends a Clear-To-Send (CTS) packet after successful receiving the RTS and deferring a short inter-frame spacing (SIFS) time. Node i, on receiving CTS, waits for SIFS and transmits its data packet. The destination node, on receiving data, waits for SIFS and replies with an acknowledgement (ACK). Node i must wait for a DCF inter-frame spacing (DIFS) time before it can service a new packet by repeating the same procedure. If node i ever fails to receive a CTS in response to its RTS, it assumes there to be a collision and resorts to the binary exponential backoff algorithm to set its contention window to $CW_i = \min\{2 \cdot CW_i,\ CW_{max}\}$. Any node overhearing an RTS or CTS defers their transmission for the indicated data transmission length.

As all nodes always start with the same CW_{min} in DCF, they essentially compete for medium access with an equal priority. The average time for each node to successfully complete a transmission is thus expected to be the same. However, this is not desirable in providing differentiated delay assurances in such networks. Consider two nodes with different amounts of traffic arrival. With the same access priority, the node with more arrival will experience a longer queue. Since it takes the same time for a node to transmit a packet, packets in the longer queue will have a higher queueing delay. In a multihop network where nodes forward packets for each other, we contend that it is undesirable and unfair for applications to have higher delays on nodes with more traffic.

This situation can be resolved if multiple priorities are provided in medium access. Ideally, when nodes compete for medium access, the node with more urgent packets should be able to transmit first with a higher medium access priority. This requires both a medium access protocol that provides multiple priorities and a mechanism that determines the access priority for each node. IEEE 802.11e extends IEEE 802.11 DCF to have multiple levels of priorities with in terms of Access Categories (AC's) [15]. Each AC i has its individual transmission queue, minimum contention window $CWmin_i$, and Arbitration IFS $AIFS_i$. IEEE 802.11e is not completely standardized and it is not clear how its different priorities are to be provisioned. In this study, we consider three different priorities and each priority has a distinct CW_{min}. At any given time, a node chooses one priority for transmission. As part of our proposed solution, the medium access priority will be determined such that the NPDD service differentiation is achieved.

III. End-to-end Throughput Assurance in Multihop WLAN's

A. The Network Model

We consider a multihop WLAN hotspot with an AP being the Internet gateway for mobile nodes. Nodes enter or leave the network at will. They also move around in a geographic area in the vicinity of the AP. Nodes need not be in the radio range of the AP if there exists a route to the AP through other nodes. Applications are hosted by these nodes with uplink or downlink end-to-end communications going through AP, while an underlying routing protocol determines the end-to-end route for each flow. The multihop network is based on IEEE 802.11, where all nodes and AP access a shared medium with DCF. IEEE 802.11e with three medium access priorities is also assumed.

B. The NPDD Service Model

The NPDD service model 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

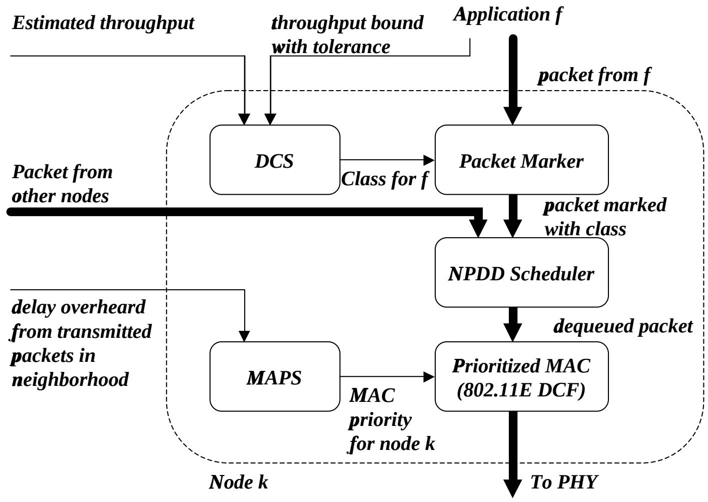


Fig. 2. End-to-end throughput assurance mechanism based on DCS and NPDD.

route between them. NPDD for a multihop WLAN is described as follows:

Let $1 = \delta_1 > \delta_2 > \cdots > \delta_N > 0$ *be* N *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.*

C. The End-to-end Throughput Assurance Problem

In this network, the end-to-end throughput assurance problem is formulated as follows. A TCP application f at a node k specifies a desired end-to-end throughput computed over its connection duration. The network strives to meet this bound but does not guarantee it.

IV. Proposed Mechanisms

The end-to-end throughput assurance is achieved with dynamic class selection (DCS) among the NPDD service classes. At each node, the mechanisms shown in Figure 2 are implemented. Each packet from an application is marked with the class determined by a DCS agent for the application. Marked packets, either from the packet marker or from other nodes, are serviced by the NPDD Scheduler and the prioritized MAC. The MAC priority is determined by the Medium Access Priority Selection (MAPS) mechanism. The NPDD Scheduler, the MAPS, and the prioritized MAC together realize the NPDD service model in a multihop WLAN hotspot.

Every Γ seconds, DCS for application f computes class $c((k+1)\Gamma) = \mathcal{C}(c(k\Gamma), T_f(k\Gamma), \hat{T}_f, \Phi_f))$.

k: Index of current period.
$T_f(k\Gamma)$: Current throughput estimate.
$\hat{T}_f$: Throughput bound of f.
Φ_f: Throughput tolerance of f.
N: Maximum NPDD class.

$\mathcal{C}(c(k\Gamma), T_f(k\Gamma), \hat{T}_f, \Phi_f))$
{
    $c(0) = 0$;
    if $T_f(k\Gamma) < \hat{T}_f$ for K_I consecutive periods,
        $c((k+1)\Gamma) = \min\{c(k\Gamma) + 1, N\}$;
    else if $T_f(k\Gamma) > \hat{T}_f + \Phi_f$ for K_D consecutive periods,
        $c((k+1)\Gamma) = \max\{c(k\Gamma) - 1, 1\}$;
    else
        $c((k+1)\Gamma) = c(k\Gamma)$;

    return $c((k+1)\Gamma)$;
}

Fig. 3. The DCS algorithm.

The mechanism is based on TCP throughput model's dependency on RTT. Given a TCP flow's maximum congestion window size W_{max}, its end-to-end throughput T admits the relationship:

$$T \propto \frac{W_{max}}{RTT} \tag{4}$$

[14]. The NPDD service classes provide a set of proportional per-hop delays and thus, a set of proportional end-to-end delays as well as proportional RTT's along an end-to-end route. As a result, the service classes are able to provide proportional throughputs for end-to-end TCP applications. The following sections describe the implementation of DCS, the NPDD Scheduler, and MAPS at each node.

A. Dynamic Class Selection

Each application is serviced by one DCS agent. DCS makes periodic class selection decisions every Γ seconds for the following period. At the k_{th} period, four inputs are considered: the current class $c(k\Gamma)$, the current throughput estimate $T_f(k\Gamma)$, the throughput bound $\hat{T}_f$, and its tolerance Φ_f. The accumulative session throughput is estimated every period by observing ACK packets. Figure 3 presents the pseudo-code.

At the end of period k, the class for period $k+1$ is determined. If throughput estimate $T_f(k\Gamma)$ is less than the desired bound $\hat{T}_f$ for K_I consecutive periods, DCS increases the class by 1. On the other hand, if $T_f(k\Gamma)$ is *overly satisfied* and exceeds the bound by Φ_f for K_D consecutive periods, DCS will decrease the class by 1. Otherwise, the class remains the same. K_I and K_D are positive integer parameters for controlling the rate of class *increase* and *decrease*, respectively. K_I and K_D should be carefully chosen such that they are small enough for applications to achieve their desirable throughput soon enough; at the same time, they should be large enough for TCP throughput to reach a steady state before further class changes occur. Applications' sensitivity to pricing can also be reflected in K_I and K_D. A cost-aware application would prefer lower classes and tend to have larger K_I and smaller K_D, and vice versa.

Class changes of a flow in the NPDD service model changes the *absolute delay* of each class. It is analyzed in [1] for the proportional delay differentiation (PDD) service model, which is equivalent to NPDD on one single node with constant link capacity (a wireline node), that a class increase of one flow always results in increased average delays in all classes, and vice versa. Intuitively, all flows make independent decisions and are competitive in nature. An analytical analysis of the competition of multiple DCS-controlled flows are out of the scope of this paper. In this paper, we demonstrate with simulations that the mechanism does converge most of the time when the network is not overloaded. At times when the network is overloaded, some flows can not achieve their bounds even with the highest class. In such cases, the flows will remain in the highest class until the congestion is resolved. Further mechanisms such as admission control and congestion resolution are possible for future investigations.

B. NPDD Scheduler

The NPDD Scheduler services packets in N classes and realizes proportional average per-hop delays among them locally at each node. The scheduler is work-conserving, and the Waiting Time Priority (WTP) algorithm [1] is adopted. With WTP, each class is serviced with a separate First-In-First-Out (FIFO) queue. The head-of-line packet of a class i is assigned a waiting time priority $\tilde{w}_i(t)$ and the scheduler always schedules the highest priority head-of-line packet for transmission.

Specifically, let $B(t)$ denote the set of classes that have packets waiting for transmission at time t. Let $w_i(t)$ denote the time the class i head-of-line packet has waited in its queue. The waiting time priority $\tilde{w}_i(t)$ at time t is defined as

$$\tilde{w}_i(t) = w_i(t)/\delta_i \tag{5}$$

where δ_i is the DDP of class i. Whenever $B(t)$ is nonempty, the scheduler schedules a packet for transmission from class j such that

$$j = \arg\max_{i \in B(t)} \tilde{w}_i(t). \tag{6}$$

Intuitively, when all packets of a node are transmitted with the same waiting time priority, the NPDD proportionality is realized at this node.

C. Medium Access Priority Selection (MAPS)

Within a class, NPDD requires the same average per-hop delay be provided at all nodes in the network. This property can not be realized with the network scheduler alone. It is discussed in Section II that delay differentiation among nodes can not be realized without prioritized medium access. While the NPDD schedulers schedule packets with their waiting time priorities, the schedule must be maintained as they are transmitted by MAC. It is for this purpose, MAPS monitors these priorities and chooses the MAC priority for a node.

MAPS performs two tasks at a node k at time t. First, it estimates the node's average waiting time priority $\bar{d}_k(t)$ and the network's average waiting time priority $\bar{d}_{N,k}(t)$. Secondly, MAPS selects the MAC priority. $\bar{d}_k(t)$ is estimated as a running average of the waiting time priority of each packet transmitted at node k,

$$\bar{d}_k(t) = \alpha\tilde{w}(t) + (1-\alpha)\bar{d}_k(t), \tag{7}$$

where $\tilde{w}(t)$ is the waiting time priority of the packet just transmitted. To estimate the network average $\bar{d}_{N,k}(t)$, each transmitted packet carries two pieces of information: the packet's priority $\tilde{w}(t)$ and the sending node q's estimate of network average $\bar{d}_{N,q}(t)$. As node k overhears the packet being transmitted by its neighbor node q, it updates its estimate

$$\hat{d}_{N,k}(t) = \gamma\tilde{w}(t) + \kappa\hat{d}_{N,q}(t) + (1-\gamma-\kappa)\hat{d}_{N,k}(t), \tag{8}$$

where γ and κ are weighting factors and $\gamma + \kappa = 1$. With the estimated priorities, MAPS computes the index

$$I_k(t) = \frac{\hat{d}_k(t)}{\hat{d}_{N,k}(t)}. \tag{9}$$

Given P levels of MAC priorities, P parameters are defined for MAPS as $0 < \epsilon_1 < \epsilon_2 < ... < \epsilon_P = \infty$. MAPS assigns priority r to node k at time t if and only if $\epsilon_{r-1} \leq I_k(t) < \epsilon_r$, where $\epsilon_0 = 0$. Intuitively, as $I_k(t)$ approaches 1, the NPDD proportionality holds across all nodes in the network.

Scheme	*DCS-NPDD-MAPS*	*Strict Priority*	*Baseline*
TCP throughput tolerance $\Phi(x)$, x: throughput bound	$0.5x$	$0.5x$	*N/A*
UDP delay tolerance $\Delta(y)$, y: delay bound	$0.5y$	$0.5y$	*N/A*
DCS period (seconds)	2	2	*N/A*
DCS sensitivity parameters (K_I, K_D)	(1,1)	(1,1)	*N/A*
NPDD classes	4	4	*N/A*
DDP δ_i, $i \in 1, 2, 3, 4$	$[1\ \frac{1}{2}\ \frac{1}{4}\ \frac{1}{8}]$	*N/A*	*N/A*
Per-class maximum queue size (packets)	600	600	2400
MAC priorities	3	3	1
MAC $CWmin_i$, $i \in 1, 2, 3$	[217 124 31]	[217 124 31]	31
MAC $CWmax_i$, $i \in 1, 2, 3$	1023	1023	1023
MAPS ϵ_i, $i \in 1, 2, 3$	$[2\ 5\ \infty]$	*N/A*	*N/A*
MAPS $d_{N,k}$ average weights (γ, κ)	(0.1, 0.1)	*N/A*	*N/A*
MAPS d_k moving average weight α	0.9	*N/A*	*N/A*
802.11 modes	802.11e over 802.11a	802.11e over 802.11a	802.11a

TABLE I

PARAMETERS OF EVALUATED SERVICE SCHEMES.

Scheme	*Values*	
aSlotTime	$9\mu s$	
aCCATime	$4\mu s$	
aRxTxTurnaroundTime	$2\mu s$	
aSIFSTime	$16\mu s$	
aPreambleLength	$20\mu s$	(1080 bits @ 54Mbps)
aPLCPHeaderLength	$4\mu s$	(216 bits @ 54Mbps)
aPLCPDataRate	54Mbps	

TABLE II

IEEE 802.11A PARAMETERS UPDATED IN *ns-2*.

V. SIMULATION STUDIES

Simulation studies of the DCS-NPDD-MAPS throughput assurance mechanism are conducted using the network simulator ns-2 [16] with its CMU mobilenode extension. Table I summarizes all simulation parameters. In the simulations, applications are assumed to always specify their throughput or delay tolerances to be 50% of the specified bound. The DCS period and sensitivity parameters are chosen to be comparable to or larger than the average time needed for TCP throughput to stabilize. DDP's define the maximum class spacing. In the simulation, the highest class is expected to provide $\frac{1}{8}$ the delay and 8 times the throughput as the lowest class does. The aggregate queue size is equal for all schemes. For IEEE 802.11e, three minimum windows are chosen with the highest class conforming to the default window (31) in IEEE 802.11. To simulate IEEE 802.11a which is not currently supported in *ns-2*, modifications are made to its physical layer attributes as defined in [6]. The modified parameters are summarized in Table II. For multihop routing, Dynamic Source Route [2] is used.

Evaluated are three service schemes: Baseline, DCS with Strict Priority, and the proposed DCS-NPDD-MAPS schemes. In the Baseline scheme, nodes implement a single FIFO scheduler and IEEE 802.11 without priorities. The scheme provides best effort service without explicit service differentiation and assurances. It demonstrates the QoS that is to be perceived by applications in a multihop hotspot without any assurance support. The Strict Priority scheme implements 4-class strict priority schedulers and IEEE 802.11e with three priorities at each node. As strict priority schedulers always schedule higher priority packets to be transmitted first, it provides consistently superior QoS to a higher class. The proposed DCS mechanism then selects among the strict priority classes to achieve the desirable end-to-end QoS bounds. It demonstrates the QoS assurances one can achieve with consistent class ordering only, as opposed to the further properties NPDD provides. The MAC priorities in this scheme are statically mapped. The lower two classes (class 1 and 2) uses the same lowest MAC priority. Class 3 uses the second and class 4 uses the highest priority. Finally, the proposed solution is referred to as the DCS-NPDD-MAPS scheme. The following section introduces the proposed Public Hotspot Mobility model.

A. The Public Hotspot Mobility Model

We contend that the conventional random way point mobility model implemented in ns-2 does not adequately capture the anticipated mobility patterns in WLAN hotspots. In particular, in WLAN hotspots, nodes tend to arrive at the network and depart from it at will. Once they arrive, they are likely to stay at a chosen location (e.g. a seat in a coffee shop or a gate in an airport). They may move occasionally, especially if connection to the network is not present. As nodes arrive and depart at different times and stay at different locations, the multihop network topology changes accordingly. In this paper, we model this mobility pattern as follows.

Node arrivals and departures are modeled as time instances with Poisson processes with known parameters. The number of nodes arriving together at the same time instance, N_A, and the number of nodes departing together at the same time instance, N_D, are random variables with distribution functions $P_A(n)$ and $P_D(n)$ respectively where n is the number of nodes. In an arrival event, each arriving node picks a uniformly distributed random location within a predefined region around AP. This region, however, is not constrained to AP's radio range. If there exists a route to AP at a node's chosen location, it stays. Otherwise, it repeats choosing another random location until connectivity is satisfied. In a departure event, departing nodes are simply removed from the network. The remaining nodes, however, may lose connection after these nodes depart. Again, nodes without connection repeats choosing another random location until connectivity is satisfied.

It is interesting to note that, the proposed model captures most possible hotspot mobility modes with the arrival and departure nodes distribution $P_A(n)$ and $P_D(n)$. In a coffee shop scenario, customers tend to come and leave as individuals or small groups. The distributions lean toward less number of nodes per arrival. However, in airports, there can be sparse individuals checking in as well as large groups of people arriving in a plane. Departures are expected to be mostly in large groups leaving with a plane. In the following, individual arrivals and departures are used to simulate a simple coffee shop scenario.

B. Simulations

The simulations evaluate the end-to-end throughput and delay assurances for concurrent TCP and UDP applications. Three scenarios are studied. The first scenario considers a multihop hotspot with node mobility modeled with PHM. The second scenario considers a multihop hotspot with a set of constantly moving nodes. The last scenario considers a single hop hotspot. The traffic pattern is modeled as follows. For each node in the network, one TCP flow and one UDP flow are initiated. With a uniform distribution, the flows are randomly set to be either uplink or downlink. Each TCP flow randomly selects one out of three possible throughput bounds (30, 60, and 90 kbps) while each UDP flow randomly selects one out of three possible end-to-end delay bounds (0.1, 0.4, and 0.7 seconds) with uniform distributions. TCP flows have infinite backlogs and $CW_{max} = 50$ packets. UDP flows have exponentially distributed on/off intervals with mean duration $128ms$ and mean on time arrival rate $200kbps$. All packets are 512 bytes in size.

To evaluate the QoS assurances, we define the *throughput utility* as follows. For a TCP flow f with throughput bound $\hat{T}_f$ and achieved session throughput T_f, its throughput utility is

$$U_f = \min\left(1, \frac{T_f}{\hat{T}_f}\right), \tag{10}$$

which is essentially the flow's *normalized throughput* upper bounded at 1. For UDP flows, we measure the percentage of packets delivered within its bound as its *in-time delivery ratio*. Note that dropped packets are taken into account as having infinite delays.

1) Multihop Hotspots with PHM: Multihop hotspots with random node arrivals and departures are simulated using the PHM model. A 1000m by 1000m square region is simulated. The AP is located at its center with a radio range of 250m. The simulated scenario lasts for 1000 seconds with mean arrival and departure rates of 1 node per minute. 20 nodes are present as the simulation begins. Figure 4 shows the average throughput utility for applications with different throughput bounds. As expected, in all three application groups, DCS-NPDD-MAPS provides the highest utility and the Baseline ranks last. As the Baseline provides no explicit differentiation and assurance mechanisms, throughputs and corresponding utilities differ among applications as they travel along different paths; they also fluctuate with time due to network dynamics such as node mobility and traffic variations. The Baseline utilities, as seen in Figure 4, are indeed unpredictable. DCS over strict priority classes allows applications to acquire better

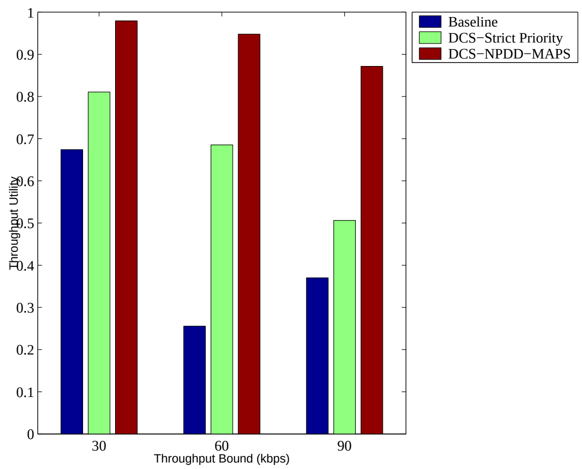
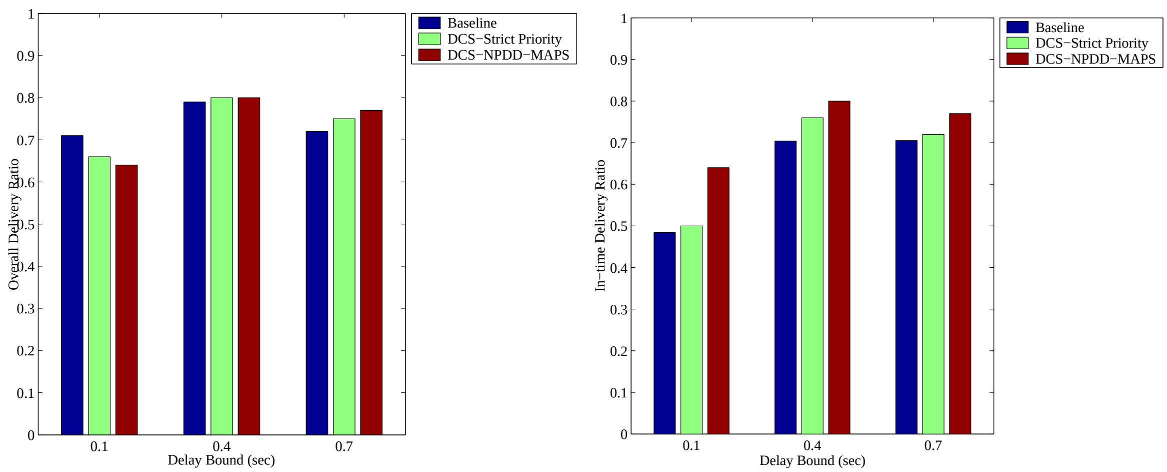


Fig. 4. Average throughput utilities in a PHM multihop hotspot.



(a) All delivered packets.

(b) Packets delivered in time.

Fig. 5. Average delivery ratios in a PHM multihop hotspot.

service with higher classes as throughputs fluctuate below satisfaction and as a result, better average utilities are achieved. Nevertheless, DCS-NPDD-MAPS provides the highest utilities among all.

The delay assurances are also evaluated. One important observation is made as we simulate such multihop hotspots with random node departures. Recall that in a multihop hotspot, nodes forward packets for each other. If a node leaves the network before it finishes forwarding all packets, the resulting packet losses can be significant. Figure 5 shows the *overall delivery ratio* (the number of received packets to the number of sent packets) and the *in-time delivery ratio* (the number of packets received within its delay bound to the number of sent packets). The amount of packet losses does not differ much among different schemes. Among these schemes, DCS-NPDD-MAPS consistently shows a higher in-time delivery ratio than others.

2) Multihop Hotspots with Moving Nodes: In this section, a multihop hotspot with 20 nodes are simulated. The nodes are located as in Figure 6 with 10 nodes in the inner circle constantly moving around the AP at $5m/s$. The simulation lasts for 1000 seconds. This scenario does not consider random node arrivals or departures but serves the main purpose of evaluating the impacts of frequent route changes as a result of the constant node movements. Figure 7 shows the achieved throughput utilities. In this highly mobile scenario, the Baseline remains unsatisfactory while the Strict Priority and DCS-NPDD-MAPS schemes both achieve substantially high throughput utilities. The in-time delivery ratios in Figure 8 are increasingly higher from Baseline, Strict Priority, to DCS-NPDD-MAPS. The decrease in all schemes'1 in-time ratios suggest that the frequent topology changes do pose a stringent challenge

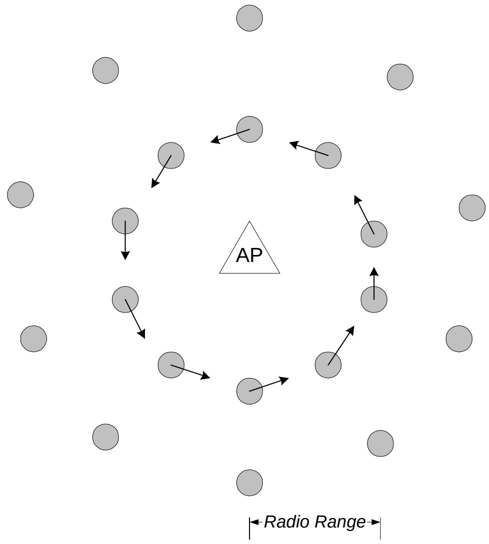


Fig. 6. A multihop hotspot with constant moving nodes.

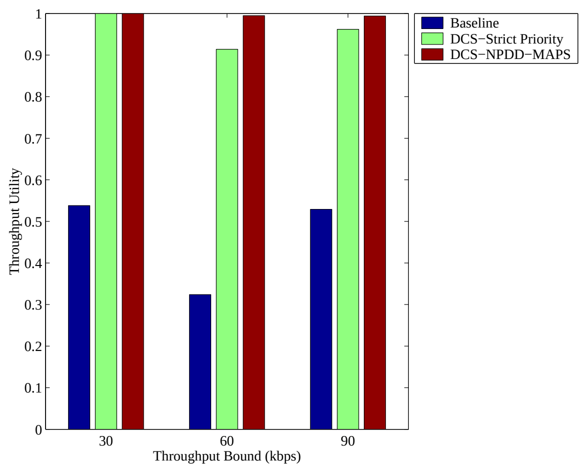


Fig. 7. Average throughput utilities in a multihop hotspot with constantly moving nodes.

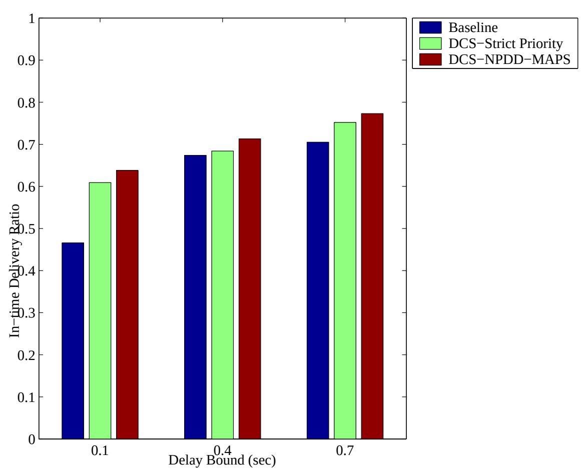


Fig. 8. Average in-time delivery ratios in a multihop hotspot with constantly moving nodes.

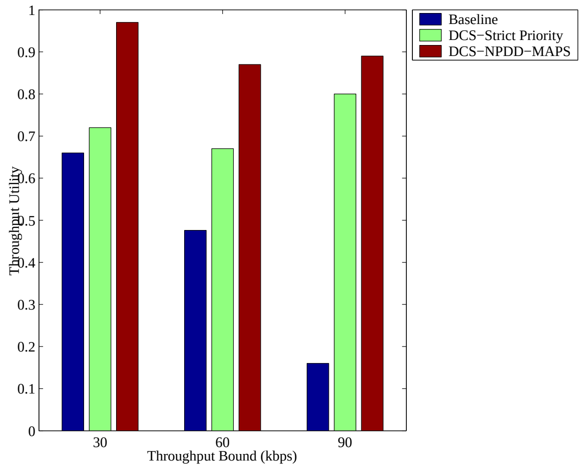


Fig. 9. Average throughput utilities in a single hop hotspot.

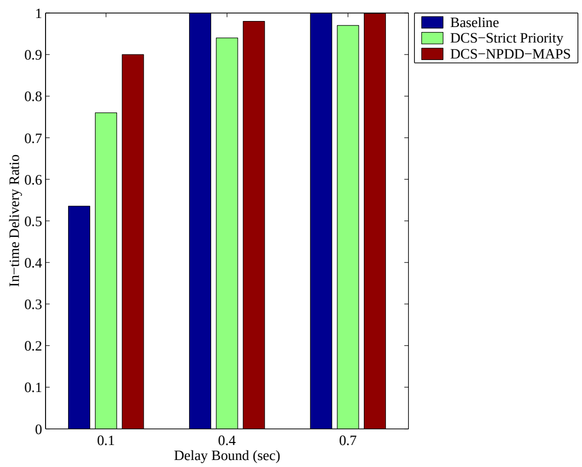


Fig. 10. Average in-time delivery ratios in a single hop hotspot.

on end-to-end delay assurances. Several observations are made. As route changes are frequent, the routing overhead becomes higher and route repairs constitute substantial traffic. Moreover, we do observe long non-optimal routes being exploited by DSR in this highly mobile network. At times when route changes aggregate a substantial amount of bursty traffic to a node, long queues and bursty drops are seen as well. Long queueing delays and packet losses both render increases in end-to-end packet delays, where the latter one is considered to be infinitely delayed.

3) Single Hop Hotspots: We have demonstrated the effectiveness of DCS-NPDD-MAPS in multihop hotspots. In this section, we evaluate the scheme in a single hop hotspot to demonstrate that the proposed solution is beneficial in single hop hotspots as well. 20 nodes are located within the AP's radio range and all nodes directly communicate with the AP. As a result, the network topology does not change as long as all nodes remain communicating with AP in one hop. The simulation lasts for 1000 seconds.

Figure 9 summarizes the average throughput utilities of these schemes. With the Baseline scheme, applications with higher throughput bounds achieve worse average utilities. The Strict Priority and DCS-NPDD-MAPS schemes, on the other hand, provide more uniform throughput utilities to applications in all groups. Figure 10 shows the delay assurances. The steep degradation in the Baseline's in-time delivery ratio for 0.1 second delay bound is expected. Without differentiation, the best effort service provides all flows with the same average delay. All flows with delay bounds above the average delay are to be satisfied and vice versa. The remaining two schemes enhance the in-time delivery ratios by allowing more urgent flows to be serviced faster with a higher class. Overall, DCS-NPDD-MAPS achieves the highest level of throughput as well as delay assurances.

VI. Conclusion

This paper addresses the challenges of providing end-to-end throughput and delay assurances concurrently in a multihop WLAN hotspot. The proposed solution is based on class selection among multiple service classes provided in the Neighborhood Proportional Delay Differentiation service model. In a highly mobile multihop WLAN hotspot, the service model provides a set of classes with per-hop delays proportional to the prespecified ratios and this proportionality holds across all nodes independent of network dynamics. As TCP applications perceive proportional RTT's among the classes, proportional throughputs are thereby provided. With simulations, the proposed class selection mechanism is shown to effectively achieve end-to-end throughput assurances in various hotspot scenarios. The throughput assurance mechanism is closely integrated with the end-to-end delay assurance mechanism we proposed earlier. Together, they provide an effective QoS assurance framework for multihop WLAN hotspots.

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