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 a wide range of 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. With NPDD, Transmission Control Protocol (TCP) based applications achieve their desired throughputs using a dynamic class selection mechanism. This approach integrates well with the NPDD-based end-to-end delay assurance mechanism proposed earlier. The integrated throughput and delay assurance mechanisms are evaluated with simulations. To better model the node mobility in a multihop hotspot, the Public Hotspot Mobility (PHM) model is proposed. Simulation results show that the proposed solution is better in meeting the desired throughputs and delays as compared with best effort and strict priority approaches.

Categories and Subject Descriptors

C.2.1 [**Computer Systems Organization**]: Computer-Communication Networks—*Network Architecture and Design*

General Terms

Algorithms, Design, Performance

Keywords

Quality of Service, Proportional Differentiation, IEEE 802.11, Medium Access, Scheduling

1. INTRODUCTION

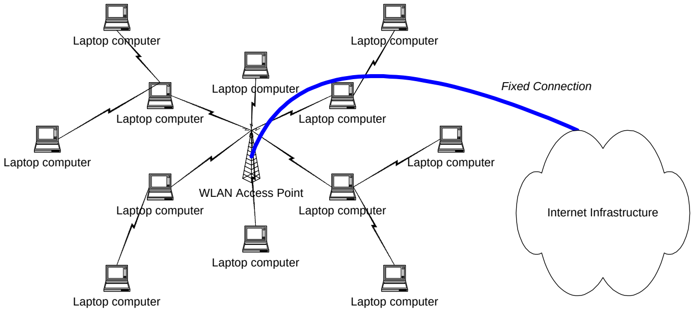

Figure 1: A multihop WLAN hotspot.

The use of wireless gateways to provide Internet access at hotspot locations such as airports and coffee shops have become commonplace in recent years. Most of such networks today are based on IEEE 802.11 standards [8, 10]. In these networks, a gateway is called an access point (AP) and two modes of connection are possible: the AP mode and the ad hoc mode. In the AP mode, all nodes directly communicate with an AP; direct communication does not take place among mobile nodes. Most existing hotspots based on IEEE 802.11b operate in the AP mode. 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). To achieve the higher rates, nodes must either stay close to an AP for direct communication in the AP mode, or they may operate in the ad hoc mode and rely on nearby neighbors for message forwarding. We thereby envision a future hotspot architecture 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 such a multihop WLAN hotspot based on IEEE 802.11.

The challenges stem from two eminent characteristics expected of a multihop hotspot WLAN:

- Node mobility.

  In a public hotspot, nodes may enter or leave a network at any time and they may wander around while there is active communication. Node mobility changes the number of nodes, the amount of traffic, and the network topology. The most critical impacts are link breaks and route changes, which inevitably result in packet losses and communication delays [7].

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- Shared medium and decentralized access.

  Nodes share the same medium in a WLAN hotspot. As nodes are not required to stay within an AP's radio range, centralized medium access scheduling at an AP is infeasible in a multihop hotspot. It is essential that nodes access the medium with a decentralized scheduling scheme such as the Distributed Coordination Function (DCF) of IEEE 802.11. Without global coordination, medium sharing among nodes is potentially unfair [22].

The dynamics due to node mobility and decentralized access of nodes often cause unacceptable variations in the quality of service (QoS) of ongoing end-to-end communications in these networks [1, 4, 14].

Several end-to-end QoS assurance techniques exist in the literature [14, 15, 17, 21]. The existing techniques, can be broadly grouped into two camps, Integrated Services (IntServ) based and Differentiated Services (DiffServ) based. IntServ based mechanisms aim to assure each flow with its specific QoS along its *specific route* with *per-flow* resource reservation at each node along the 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 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 [11] and the Assured Forwarding (AF) PHB [6]. End-to-end QoS assurances are defined as Per Domain Behaviors (PDB's) with PHB's as their building blocks [17].

There are a number of reasons to believe that the existing IntServ and DiffServ proposals are difficult to implement in a multihop wireless network. Difficulties with IntServ solutions are centered around resource reservation. As the available bandwidth for each node varies with time, it is necessary but hard for a node to estimate its available bandwidth for resource reservation. Since the medium is shared, it is also necessary that resource reservation be done with global coordination. Once reservations are made, violations may occur due to bandwidth fluctuations as well as route changes, as such reservations are pinned to a route [21]. DiffServ solutions do not perform resource reservation. DiffServ assurances, however, largely depend on available resources in a network. The EF PHB assures low queueing delays at a node if its service rate is no less than the EF traffic arrival rate. The AF PHB provides assured throughput at a node with packet priority marking and selective queue management. Packets marked with high priorities are assured to be always serviced before low priority ones. If the marking rate does not exceed the bandwidth, a throughput equal to the marking rate is assured at each node. AF alone, however, does not address end-to-end throughput assurances. Both EF and AF face a difficult resource provisioning problem in a dynamic multihop network.

In [20], we proposed the DiffServ based service called Neighborhood Proportional Delay Differentiation (NPDD) in a multihop WLAN. In the NPDD model, the network supports multiple service classes. The PHB at each node assures that the ratio of average packet delays in two different classes equals a ratio preset by the network service provider. Attractively, the PHB requirement holds independent of each node's dynamic bandwidth and traffic arrival. Based on the NPDD model, [20] 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. The integrated solution collectively serves an effective QoS (end-to-end delay and throughput) differentiation and assurance framework in a multihop WLAN.

We evaluate the proposed mechanisms with simulations. To model the node mobility characteristic of a public hotspot where individual users arrive and depart at will, the existing mobility models do not suffice. Specifically, a multihop hotspot features both random node participation and short movements during their stay. Existing random mobility models either address channel occupation times and hand-offs in the context of cellular networks [5, 16] where local movements are irrelevant in a cell, or random motion of a fixed population of nodes in ad hoc networks [12]. We thus propose the Public Hotspot Mobility (PHM) model. As shown in the paper, the model adequately captures both individual node mobility as seen in coffee shops hotspots and group mobility as seen in airport hotspots.

The remainder of the paper is organized as follows. Section 2 briefly reviews IEEE 802.11 medium access control (MAC) and IEEE 802.11e [2], its proposed extension for QoS differentiation. The significance of prioritized medium access in the proposed assurance mechanism is stated. Section 3 describes the network model, the NPDD service model, and the end-to-end throughput assurance problem. In Section 4, we describe the proposed throughput assurance mechanism. The proposed mechanism is evaluated in multihop as well as single-hop IEEE 802.11 based WLAN hotspots in Section 5. The paper concludes in Section 6.

2. IEEE 802.11 DCF AND IEEE 802.11E EDCF

IEEE 802.11 DCF provides asynchronous carrier sense multiple access with collision avoidance (CSMA/CA) at each node [8]. For CSMA, a node senses the channel to be idle before it transmits a packet. For CA, each node waits for an additional*random backoff time* before each packet transmission. Specifically, when a node k wishes to transmit a packet, it senses the channel to be idle for a minimum duration called DCF Inter-Frame Spacing (DIFS). Moreover, an additional backoff interval of B_k slots is chosen. B_k is randomly chosen with uniform distribution in the interval [0, CW_k], where CW_k is the *contention window* of node k. CW_k is set to $CW_{\min}$, which is a DCF parameter, at the beginning of time as well as after each successful transmission at node k. Beyond DIFS, for every additional slot the medium is sensed idle, B_k is decremented by 1. Whenever the medium becomes busy, B_k is frozen until the medium becomes idle for another DIFS duration. As B_k reaches 0, node k is allowed to transmit its packet. On successful receiving the packet, the receiver immediately replies with an acknowledgement (ACK). Without receiving an ACK, the sender considers the transmission to have collided. To retransmit a packet, the sender must wait for another random backoff chosen with a doubled contention window $CW_k = \min\{2 \cdot CW_k,\ CW_{\max}\}$.

To further reduce the overhead of collisions, an optional channel reservation scheme called Request-to-Send and Clear-to-Send (RTS/CTS) is defined in DCF. At the end of random backoff, node k broadcasts a tiny RTS packet instead of its data packet. RTS carries the intended receiver address and the intended data transmission length. On receiving an RTS, the receiver defers for a Short Inter-Frame Spacing (SIFS) and broadcasts a CTS packet. Tiny as well, CTS also carries the intended data transmission length. On receiving CTS, node k defers for SIFS and transmits the data packet. Finally, on successfully receiving the data, the receiver sends an ACK towards node i and ends the RTS-CTS-DATA-ACK transaction. With RTS/CTS, each node overhearing an RTS or CTS packet defers for the intended data transmission length to avoid collision. If node k ever fails to receive a CTS in response to its RTS or an ACK in response to its data, it assumes there to be a collision and resorts to the same binary exponential backoff.

As all nodes start with the same $CW_{\min}$ in DCF, they essentially compete for medium access with an equal priority. At each node, the average time to complete a transmission is expected to be the same. While this may be perceived as fair treatment to all packets in a best effort network, this is not desirable if packets must be serviced with diverse QoS requirements. Furthermore, in a multihop network where nodes forward packets for each other, the amount of arrivals may differ among nodes. Consider two nodes with different traffic arrivals. With the same access priority, the node with more arrival must experience a longer queue. Since the average packet transmission time is the same for each node, packets in the longer queue will have a higher average queueing delay.

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. In IEEE 802.11e, the Enhanced DCF (EDCF) provides multiple access priorities with multiple Access Categories (AC's) [2]. Each AC is essentially an independent DCF instance with its individual transmission queue and controllable DCF parameters including the minimum and maximum contention windows and an Arbitration Inter-Frame Spacing (AIFS). 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. In Section 4, we describe our proposed solution for medium access priority selection.

3. END-TO-END THROUGHPUT ASSURANCE IN MULTIHOP HOTSPOTS

3.1 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 the vicinity of the AP. Nodes are not required to be within the AP's radio range if there exists a route to reach the AP in multiple hops. Mobile nodes host applications with uplink or downlink end-to-end communication flows 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 and IEEE 802.11e. Three medium access priorities are assumed with the IEEE 802.11e EDCF.

3.2 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 $i < j$, $i, j \in S_{B,k}$ where $S_{B,k}$ is the set of backlogged classes at node k. The spacing between 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 *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 between all pairs of nodes* k *and* q *such that* k *and* q *belong to the same contending set. We 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.*

3.3 End-to-end Throughput Assurance

Mobile nodes host applications with end-to-end communication demands in a multihop WLAN. Applications are considered to have specific QoS requirements. Specifically, an end-to-end TCP-based application is likely to request for assurances on its end-to-end throughput performance. The end-to-end throughput assurance problem is formulated as follows:

An application f *at a node* k *forms a TCP connection with a remote destination. The application requests an assured*

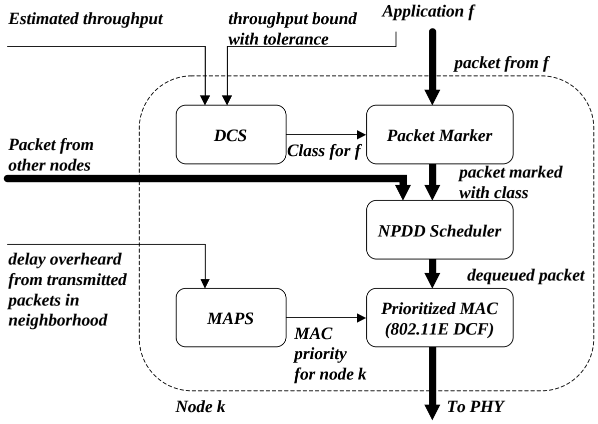

Figure 2: End-to-end throughput assurance mechanism based on DCS and NPDD.

minimum end-to-end throughput $\hat{T}_f$ *such that*

$$T_f \geq \hat{T}_f \tag{4}$$

over its connection duration. The network strives to meet this bound. The network, however, provides no hard guarantees.

4. 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. With the mechanism, each application packet is marked with the class determined by a DCS agent. Once a packet is marked at the application sender, it is serviced according to its class along its end-to-end route. At each node, packets 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.

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

$$T \propto \frac{W_{\max}}{RTT} \tag{5}$$

[18]. As NPDD assures proportional per-hop delays among classes at each node, the end-to-end delays and RTT's along a specific route are proportional among classes as well. The NPDD service classes thereby provide proportional end-to-end throughput for TCP-based applications. The following sections describe the implementation of DCS, the NPDD Scheduler, and MAPS at each node.

4.1 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 TCP ACK packets. Figure 3 presents the pseudo-code.

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Every $\Gamma$ 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 $f$.
$\Phi_f$:        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 $c((k+1)\Gamma)$;
}
```

Figure 3: The DCS algorithm.

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 [3] for the proportional delay differentiation (PDD) service model, which is equivalent to NPDD on a node with constant link capacity (a wireline node), that *a class increase of one flow results in increased average delays in all classes* and *a class decrease of one flow results in decreased average delays in all classes.* 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.

4.2 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 [3] 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 $S_B(t)$ 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

$$\tilde{w}_i(t) = w_i(t)/\delta_i \qquad (6)$$

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

$$j = \arg \max_{i \in S_B(t)} \tilde{w}_i(t). \qquad (7)$$

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

4.3 Medium Access Priority Selection (MAPS)

NPDD requires packets of the same class to have the same average per-hop delay at all nodes in the network. This property can not be realized with the network scheduler alone. In Section 2, we briefly discussed the necessity of medium access priorities in meeting diverse application delay requirements. In the proposed solution, medium access priorities are adapted at each node such that a class has the same average per-hop delay at all nodes in the network.

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,

$$\bar{d}_k(t) = \alpha \tilde{w}(t) + (1 - \alpha) \bar{d}_k(t), \qquad (8)$$

where $\tilde{w}(t)$ is the waiting time priority of the packet just transmitted and α is the weighting factor of the running average. 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

$$\hat{d}_{N,k}(t) = \gamma \tilde{w}(t) + \kappa \hat{d}_{N,q}(t) + (1 - \gamma - \kappa) \hat{d}_{N,k}(t), \qquad (9)$$

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

$$I_k(t) = \frac{\hat{d}_k(t)}{\hat{d}_{N,k}(t)}. \qquad (10)$$

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, each node has an average waiting time priority close to the network average. It can be shown with Equation 6 that nodes with the same average waiting time priority must have the same per-hop delay in the same class. The NPDD proportionality thus holds across all nodes in the network.

5. SIMULATION STUDIES

The proposed throughput assurance mechanism is integrated with the delay assurance mechanism based on NPDD. With simulations, the integrated solution is evaluated and compared with two conventional approaches, *best effort* and *strict priority*. Denoted as the Baseline scheme, the best effort service uses a FIFO scheduler and the IEEE 802.11 DCF at each node. The Baseline performance represents the QoS perceived in existing IEEE 802.11 based WLAN hotspots. The Strict Priority scheme is based on a strict priority scheduler with four classes and the IEEE 802.11e EDCF with three medium access priorities. As strict priority schedulers always schedule higher priority packets to be transmitted first, it provides consistently superior QoS to a higher class. We apply our proposed DCS mechanism upon the strict priority classes for an application to find a class meeting its desirable end-to-end QoS bounds. It demonstrates the QoS assurances achievable with consistent class ordering but without the NPDD proportionality. Strict priority classes are statically mapped to the MAC priorities (Class 1, 2→Priority 1, Class 3→Priority 2, Class 4→Priority 3). Finally, the proposed solution is referred to as the DCS-NPDD-MAPS scheme. All simulations are conducted using the network simulator *ns-2* [19] with its CMU mobilenode extension.

Table 1 summarizes all simulation parameters. The TCP throughput and delay tolerances define the margin for class decreases in DCS. In our simulations, all tolerances are set to be 50% of the throughput or delay bound. The DCS period and sensitivity parameters control the rate of class changes. The values are set to allow applications sufficient time to obtain accurate end-to-end QoS estimations. QoS spacings are defined by DDP's. Based on the chosen DDP's, the highest class is expected to provide $\frac{1}{8}$ the delay and 8 times the throughput of the lowest class. While the Baseline has a single class and the remaining two schemes have four, an equal aggregate queue size is provisioned for all schemes. To simulate IEEE 802.11a which is not currently supported in *ns-2*, modifications are made to its physical layer attributes as defined in [9]. The modified parameters are summarized in Table 2. Dynamic Source Route [13] is the adopted ad hoc routing protocol.

5.1 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.

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 $CW_{\min,i}$, $i \in 1, 2, 3$	[255 127 31]	[255 127 31]	255
MAC $CW_{\max,i}$, $i \in 1, 2, 3$	1023	1023	1023
MAPS ϵ_i, $i \in 1, 2, 3$	$[0.4\ 0.6\ \infty]$	*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 1: Parameters of evaluated service schemes.

Scheme	*Values*	
aSlotTime	$9\mu s$	
aCCATime	$4\mu s$	
aRxTxTurnaroundTime	$2\mu s$	
aSIFSTime	$16\mu s$	
aPreambleLength	$20\mu s$	(120 bits @ 6Mbps)
aPLCPHeaderLength	$4\mu s$	(24 bits @ 6Mbps)
aPLCPDataRate	6Mbps	
BasicRate	6Mbps	
DataRate	54Mbps	

Table 2: IEEE 802.11a Parameters Updated in *ns-2*.

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 an AP. This region, however, is not constrained to the AP's radio range. If there exists a route to the AP from a node's chosen location, it stays. Otherwise, it has to repeat 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, a node without connection has to repeat 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.

5.2 Simulations

The simulations evaluate end-to-end throughput and delay assurances for concurrent TCP and UDP applications. Three scenarios are studied. The first scenario considers a multihop hotspot where node mobility is modeled with PHM. The second scenario considers a multihop hotspot with a fixed number of nodes constantly moving around the network. The last scenario considers a single-hop hotspot, which is typical of most WLAN hotspots today. The traffic pattern is modeled as follows. Each node initiates a TCP flow and a UDP flow between itself and the AP whenever it is present in the network. The flows are either uplink or downlink selected in random with uniform distribution. 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 are infinitely backlogged with a maximum window of $W_{\max} = 50$ packets. UDP flows have exponentially distributed on/off intervals with mean duration $128ms$ and a mean on-time arrival rate $200kbps$. All packets are 512 bytes in size.

Throughput assurances are evaluated in terms of *throughput utility* defined as follows. For a TCP flow f with throughput bound $\hat{T}_f$ and achieved session throughput T_f, its throughput utility is

$$U_f = \min\left(1, \frac{T_f}{\hat{T}_f}\right). \tag{11}$$

Throughput utility is essentially the *normalized throughput* of a flow. Upper bounded by 1, a user has the same satisfaction with any throughput above its specified bound. Delay assurances for a UDP flow are evaluated with its *in-time delivery ratio*, i.e., the percentage of packets delivered with end-to-end delays within its bound. Packets dropped en route are considered as packets with infinite delays.

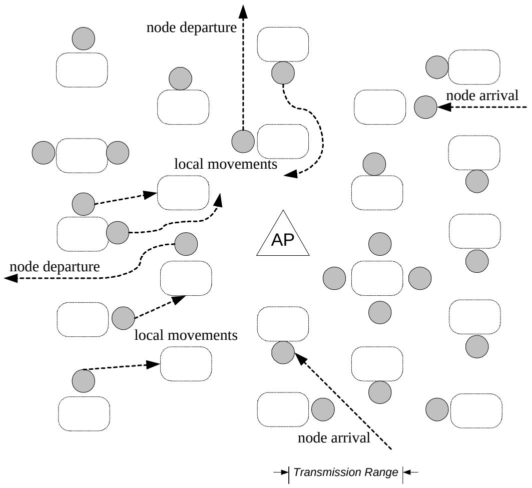


Figure 4: A multihop hotspot modeled with PHM. Nodes are shown in circles beside square tables.

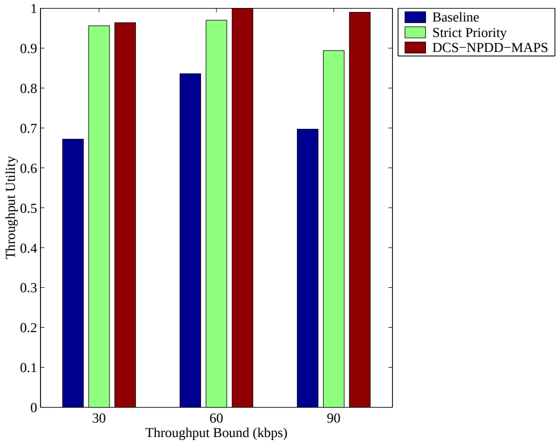
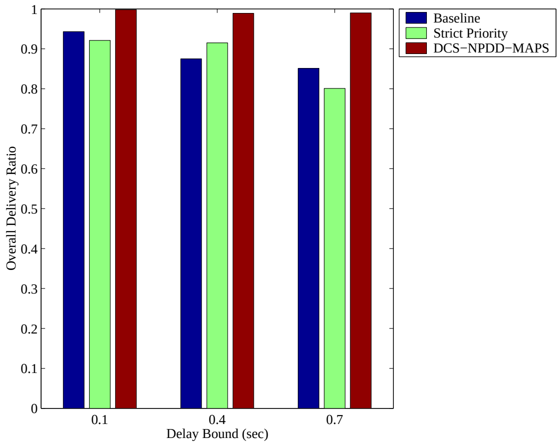
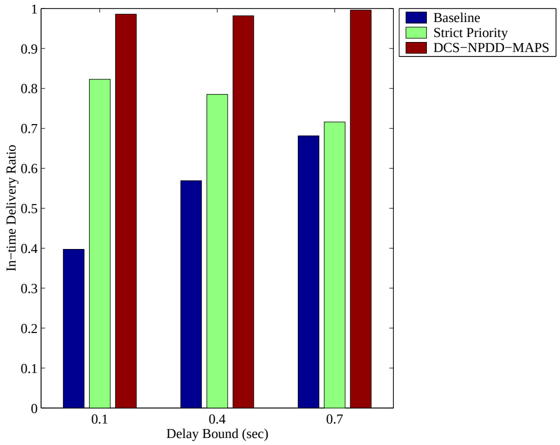


Figure 5: Average throughput utilities in a PHM multihop hotspot.



(a) Packets received over packets sent.



(b) Packets received in time over packets sent.

Figure 6: Average delivery ratios in a PHM multihop hotspot.

5.2.1 Multihop Hotspots with PHM

Random node arrivals and departures are simulated using the PHM model in this scenario. In a 1000m by 1000m square region, the AP is located at the center with a radio range of 250m. Figure 4 illustrates one snapshot of a coffee shop scenario. Mobile users are drawn as circles sitting beside square-shaped tables. In Figure 4, two nodes arrive at the network and stay at locations with network connectivity. On the other hand, two nodes depart from the network leaving a number of nodes out of network connection. To regain connection, nodes move locally to new locations closer to the AP or a connected user. The simulated scenario lasts for 1000 seconds with mean arrival and departure rates of 1 node per minute. Nodes are assumed to arrive and depart individually, i.e., $N_A = N_D = 1$ and $P_A(1) = P_D(1) = 1$. 20 nodes are present in the network as the simulation begins. On the average, there are around 20 to 30 concurrent flows present in the network most of the time.

Figure 5 shows the average throughput utilities grouped according to the three different throughput bounds. Each bar in a group represents the average utility achieved with one scheme. The Baseline exhibits the least and the most unpredictable utilities for the diverse TCP applications. The performance degradation is attributed to network topology changes and traffic variations. Apparently, at times of path changes and congestion, applications are unable to maintain desirable throughputs without QoS differentiation. Both the Strict Priority and the DCS-NPDD-MAPS schemes respond to network changes by means of class adaptation. The Strict Priority does present consistently better utilities than the Baseline, while DCS-NPDD-MAPS provides the highest utility for applications with all throughput requirements.

As is mentioned earlier, packets lost en route are considered as infinitely delayed. In a highly congested network, packet losses can severely degrade the overall delay assurance. Take this scenario for example, Figure 6 (a) shows the overall packet delivery ratio, which is the percentage of

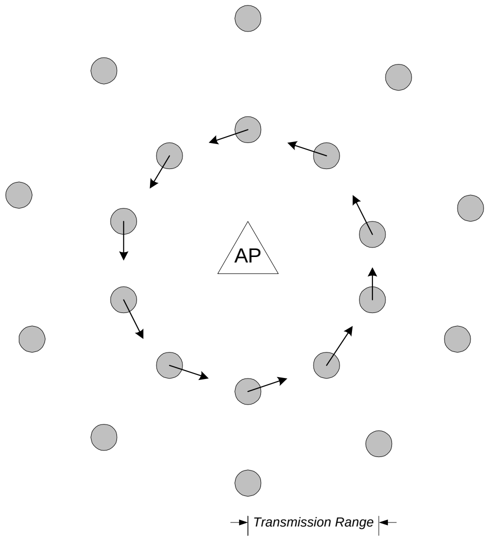


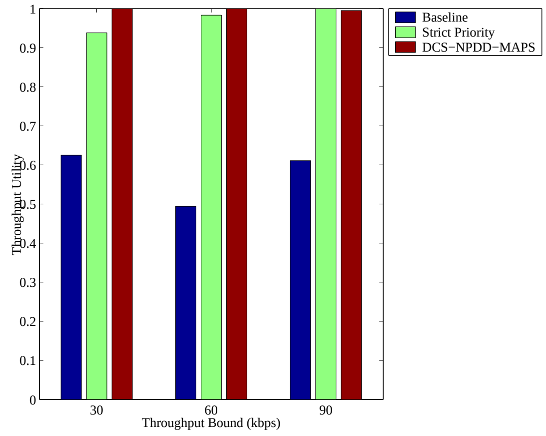
Figure 7: A multihop hotspot with constant moving nodes.

packets delivered from senders to receivers without worrying about the delay bounds. Figure 6 (b), on the other hand, shows the percentage of packets delivered from senders to receivers in time. It is demonstrated that DCS-NPDD-MAPS provides a higher delivery ratio with and without considering the delay constraints. While the Baseline scheme shows a clear degradation trend in in-time delivery ratios with tighter delay bounds, the Strict Priority and DCS-NPDD-MAPS schemes provide more uniform performance for applications with diverse delay requirements.

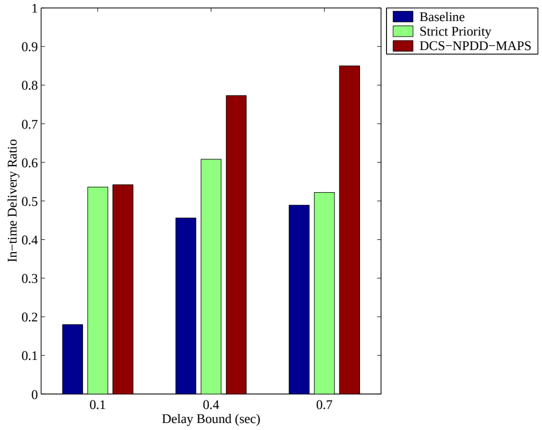
5.2.2 *Multihop Hotspots with Moving Nodes*

The scenario considers a fixed number of nodes constantly moving around while they actively communicate with an AP. As shown in Figure 7, 20 nodes are placed in two circles around the AP. Nodes in the outer circle can not directly communicate with the AP but rely on multihop forwarding. The constant movement is modeled with the inner nodes moving counterclockwise around the AP at $5m/s$. The imaginary node movement is rather regular, but it creates frequent topology and route changes for out evaluation purpose. The simulation lasts for 1000 seconds.

Figure 8 (a) shows the achieved throughput utilities. In this highly mobile scenario, the Baseline remains unsatisfactory while the Strict Priority and DCS-NPDD-MAPS schemes achieve substantially high throughput utilities. The in-time delivery ratios are, however, obviously impaired by the constant node mobility. As seen in Figure 8 (b), DCS-NPDD-MAPS still poses significantly higher in-time delivery ratios than the other two for applications with 0.4-second and 0.7-second delay bounds. For applications with a 0.1-second delay bound, Strict Priority and DCS-NPDD-MAPS are similar in performance. The frequent changes in network topology force a large number of packets to be held at nodes during periods of route breaks and route repairs. Such overheads are inevitable and can not be fully compensated with either scheduling scheme. Moreover, route repairs constitute substantial traffic that induces further network congestion. It is observed that long non-optimal routes are often 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.



(a) Average throughput utilities



(b) Average in-time delivery ratios

Figure 8: Assurances in a multihop hotspot with constantly moving nodes.

5.2.3 *Single-Hop Hotspots*

We have demonstrated the effectiveness of DCS-NPDD-MAPS in multihop hotspots. In this section, we evaluate its performance in a single-hop hotspot typical of most WLAN hotspots today. As shown in Figure 9, 20 nodes are located within the AP's radio range and all nodes directly communicate with the AP. In fact, as all nodes directly communicate with the AP, the actual locations of the nodes do not affect the network topology. Node mobility are irrelevant in such a topology. The simulation lasts for 1000 seconds.

Figure 10 (a) summarizes the achieved throughput utilities. With the Baseline scheme, applications with higher

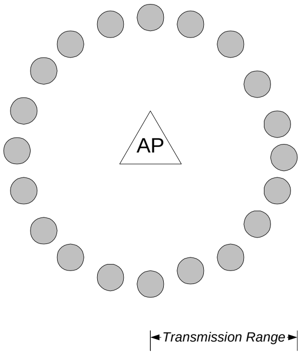


Figure 9: A single-hop hotspot with 20 stationary nodes.

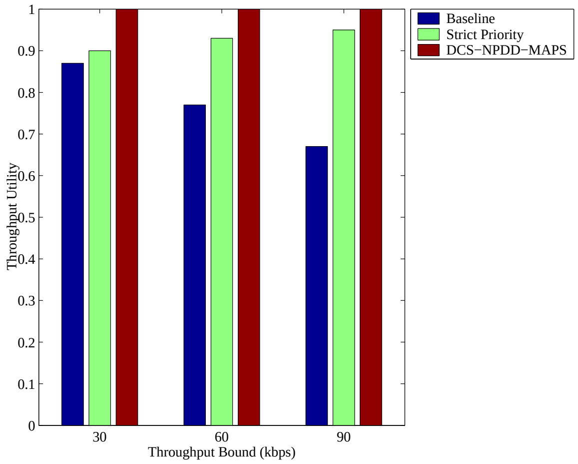
throughput bounds achieve worse average utilities. The Strict Priority and DCS-NPDD-MAPS schemes, on the other hand, provide uniformly higher throughput utilities to applications with different bounds. Figure 10 (b) shows the delay assurances. The steep degradation in the Baseline's in-time delivery ratio for applications with a 0.1-second delay bound is observed. 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 earlier with a higher class. Overall, DCS-NPDD-MAPS achieves the highest level of throughput as well as delay assurances.

5.2.4 *Packet Distribution*

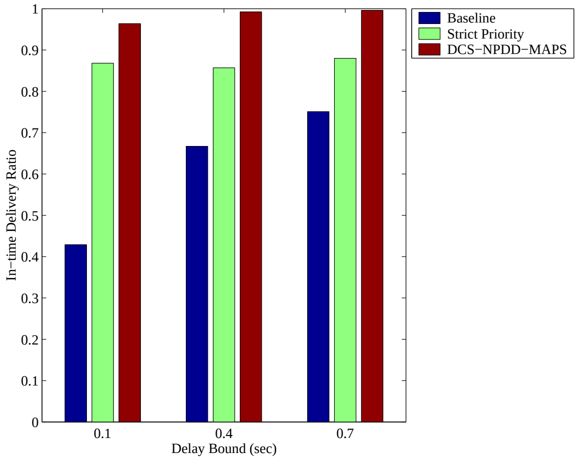
Table 3 summarizes the amount of packets generated in all simulations and the respective class distribution. While the Baseline scheme has one single class, the class distribution for Strict Priority and DCS-NPDD-MAPS depends on class adaptation of the applications. Consistently, we see that less of high priority packets have been generated with DCS-NPDD-MAPS. That is, DCS-NPDD-MAPS has achieved its superior performance using less of high priority packets, which indicates a more efficient network utilization. It is also observed that more packets have been serviced by DCS-NPDD-MAPS in the same time duration. Since UDP sources have a fixed data rate, the higher throughput reflects the better throughput for TCP applications with DCS-NPDD-MAPS.

6. 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 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 pre-defined 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.



(a) Average throughput utilities



(b) Average in-time delivery ratios

Figure 10: Assurances in a single-hop hotspot.

7. ACKNOWLEDGEMENTS

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	Multihop PHM				
	Packets	Class 1 (%)	Class 2 (%)	Class 3 (%)	Class 4 (%)
Baseline	506383	100.0	0.0	0.0	0.0
Strict Priority	654112	69.1	14.0	8.1	8.8
DCS-NPDD-MAPS	1133509	92.6	1.0	0.7	5.7

	Constant Mobility				
	Packets	Class 1 (%)	Class 2 (%)	Class 3 (%)	Class 4 (%)
Baseline	659100	100.0	0.0	0.0	0.0
Strict Priority	791715	26.0	12.6	16.6	44.8
DCS-NPDD-MAPS	952050	65.0	9.0	5.5	20.5

	Single-hop				
	Packets	Class 1 (%)	Class 2 (%)	Class 3 (%)	Class 4 (%)
Baseline	843626	100.0	0.0	0.0	0.0
Strict Priority	934358	77.4	12.2	8.5	6.9
DCS-NPDD-MAPS	1557092	91.2	2.4	0.1	6.3

Table 3: Packets generated in simulations and their class distribution.

as necessarily representing the views of funding agencies. The authors would also like to thank the anonymous reviewers for their valuable comments and corrections to this work.

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