

Performance Impact of Inter-Layer Dependence in Infrastructure WLANs

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Abstract

Widespread deployment of infrastructure WLANs has made Wi-Fi an integral part of today's Internet access technology. Despite its crucial role in affecting end-to-end performance, past research has focused on MAC protocol enhancement, analysis and simulation-based performance evaluation without sufficient consideration for modeling inaccuracies stemming from inter-layer dependencies, including physical layer diversity, that significantly impact performance. We take a fresh look at IEEE 802.11 WLANs, and using experiment, simulation, and analysis demonstrate its surprisingly agile performance traits. Our findings are two-fold. First, contention-based MAC throughput degrades gracefully under congested conditions, enabled by physical layer channel diversity that reduces the effective level of MAC contention. In contrast, fairness degrades and jitter increases significantly at a critical offered load. This duality obviates the need for link layer flow control for throughput improvement. Second, TCP-over-WLAN achieves high throughput commensurate with that of wireline TCP under saturated conditions, challenging the widely held perception that TCP throughput fares poorly over WLANs when subject to heavy contention. We show that TCP-over-WLAN prowess is facilitated by the self-regulating actions of DCF and TCP feedback control that jointly drive the shared channel at an effective load of 2-3 wireless stations, even when the number of active stations is large. We show that the mitigating influence of TCP extends to unfairness and adverse impact of dynamic rate shifting under multiple access contention. We use experimentation and simulation in a complementary fashion, pointing out performance characteristics where they agree and differ.

Keywords: Wireless communication, access schemes, physical layer diversity, TCP-over-WLAN performance, experimentation vs. simulation

I. INTRODUCTION

A. *Background and Motivation*

Widespread deployment of wireless local area networks (WLANs) at campuses, enterprises, residential areas, and commercial hotspots has made IEEE 802.11 WLANs [4], also referred to as Wi-Fi when complying with industry interoperability standards, a key component of today's integrated wireline/wireless Internet. As with ALOHA [5] and Ethernet [30] in the 1970s, the advent of WLANs in the late 1990s has spurred research aimed at understanding its properties, including performance analyses of IEEE 802.11 CSMA/CA [9], [12], fair scheduling [28], [40], capacity analyses of ad hoc WLANs [15], [16] (and hybrid extensions [26], [27]), and measurement-oriented studies [7], [25], [37]. The capacity of CSMA/CD Ethernet was not without controversy—Boggs et al. [10] discuss the wide ranging performance perceptions of the DIX and IEEE 802.3 10Base5 Ethernets deployed in the 1980s—but the subsequent evolution to switched technology, with CSMA/CD preserved for backward compatibility, rendered many of the earlier issues moot. This is not the case for IEEE 802.11 WLANs as physical shielding of the wireless transmission medium from interference and localization of contention at a switch are infeasible. WLAN performance is influenced by three main variables: mobility, channel noise, and multiple access contention. Mobility across access points (APs) in an extended service set is facilitated by reassociation-based handoff augmented by legacy link layer forwarding over wireline distribution networks. Mobility support across extended service sets through Mobile IP, at the present, is rarely instituted—even within a single organization—due to security concerns and insufficient application demand. Mobility support across domains is hindered by administrative boundaries and policy barriers. Channel noise in the unlicensed 2.4/5 GHz ISM/U-NNI bands can be a problem, especially when the distance between wireless station and AP is far. Current remedies include multi-rate support in physical layer modulation, with adaptive rate selection left to vendor discretion.

The focus of this paper is on WLAN performance in hot spots—the dominant mode of WLAN usage today—where performance degradation from contention-based multiple access is the key concern. In several respects, there is ambiguity about the performance of WLANs today as there was about the capacity of Ethernet in the 1980s. For example, in [9] it is shown that IEEE

802.11 DCF system throughput significantly declines as offered load is increased. The analysis and simulation, however, do not consider the effect of physical layer channel diversity (also called multiuser diversity [23], [39]) that mitigates throughput degradation. Performance discrepancies between modeling/simulation and experimentation with respect to transmission range and capture effect have been discussed in [6], [24]. In [41] it is shown that 802.11b throughput decreases from above 6 Mbps to below 2 Mbps as the number of stations is increased from 1 to 14. The performance results are stated as validating the 802.11 capacity analysis carried out in [11]. The results in [41] are difficult to replicate, that is, unless dynamic rate shifting is activated—the default case—which easily confuses collision with channel noise. In [42], [43] it is indicated that forward TCP data traffic can collide with reverse acknowledgment traffic, “dramatically” increasing the frame error rate which may be more pronounced in pre-802.11 WLAN cards where MAC level retransmission is absent. In [17], an enhanced DCF protocol called DCF+ is proposed to address this problem. We show that this potential TCP data/ack collision problem does not materialize due to the self-regulating actions of DCF and TCP feedback control. One of the goals of this paper is to help clarify some of the ambiguities surrounding WLAN performance through delineation of wireless and wireline features, incorporation of the impact of inter-layer dependencies, including those stemming from physical layer channel diversity, that impact performance.

B. New Contribution

The contribution of this paper is two-fold, discussed in two parts: DCF MAC layer performance and TCP-over-WLAN performance. First, we show that contention-based DCF throughput degrades gracefully as offered load or the number of wireless stations is increased. This is enabled by physical layer channel diversity that reduces the effective level of MAC layer contention, a form of multiuser diversity whose persistent manifestation in IEEE 802.11 WLANs DCF is able to exploit. This obviates the need for recently proposed link layer flow control schemes [20], [44] aimed at preventing MAC throughput degradation. We also show that empirical evidence of drastic throughput degradation of IEEE 802.11b WLANs under moderate load [19], [41] are likely to stem from the influence of dynamic rate shifting implemented in most WLAN cards,

which suffer from the problem of not being able to effectively distinguish collision from channel noise. Downshifting to fallback rates (e.g., 5.5, 2 and 1 Mbps in 802.11b) helps when increased distance or channel noise results in small SNR, but is ineffective—in fact, detrimental—when collisions are the primary cause of frame errors. In contrast to throughput, MAC layer fairness degrades and jitter increases significantly at a critical offered load, and can benefit from traffic controls aimed at operating the system outside the saturation region.

Second, we show that TCP-over-WLAN achieves high throughput commensurate with that of wireline TCP, even under saturated conditions where the number of wireless stations is very large. We show that TCP-over-WLAN prowess is facilitated by the self-regulating actions of DCF and TCP feedback control, which jointly drive the shared baseband medium at an effective load of 2–3 wireless stations. As a consequence, the TCP data/ack collision problem raised in [17], [42], [43] does not manifest as a real performance concern. TCP-over-WLAN also mitigates persistent unfairness due to physical layer channel diversity and throughput degradation stemming from dynamic rate shifting. We evaluate TCP-over-WLAN performance by analyzing a Markov chain over the state space counting the number of backlogged stations. We show a strong negative drift in the Markov chain which is established by inferring transition rates from measurement traces, both from experiment and simulation. We identify situations—analogue to wireline TCP with mismatched low bandwidth access links [35]—where buffer overflow at the gateway or AP may become a dominant factor. We show that traffic controls utilizing receiver-side advertised window and virtual delay control can alleviate the essentially wireline bottleneck problem.

The remainder of the paper is organized as follows. In the next section, we give the technical set-up. This is followed by Section III which discusses the performance properties of IEEE 802.11b DCF. Section IV studies TCP-over-WLAN performance including control issues. We conclude with a discussion of our results.

II. SYSTEM MODEL

A. Infrastructure WLAN Environment

We consider an integrated wireless/wireline IP internetwork where access networks are comprised of IEEE 802.11 infrastructure WLANs that service wireless hosts. An access point

(AP) may be connected to other APs by a wireline distribution network—typically one or more Ethernet switches—that is then connected to the Internet via a wireline access link. Figure 1 depicts the components of such a network system. Our focus is on the wireless access

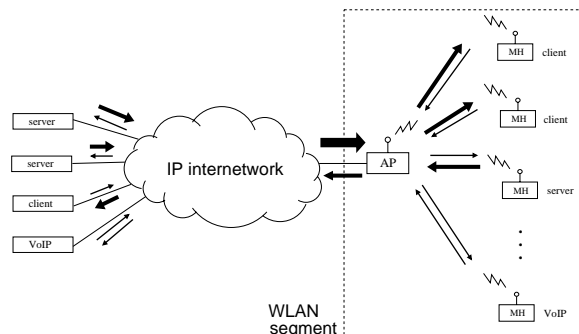


Fig. 1. Wireless/wireline IP internetwork with IEEE 802.11 infrastructure WLAN segment.

segment representative of hot spots deployed at coffee houses, airport lounges, SOHOs, and residential home networks. Typical last mile access technology include broadband cable/DSL and DS3/OC3 lines for small-to-medium enterprises. We model the wireless/wireline network system as a dumbbell network where n wireless hosts access the wireline network through an AP—collectively forming a basic service set (BSS)—which is connected to a router that, in turn, connects n wireline hosts. A canonical configuration treats the wireless hosts as clients that communicate with servers on the wireline side. In $ns-2$ simulations, the dumbbell configuration also serves as the physical topology.

B. Experimental Set-up

We connect an Enterasys RoamAbout R2 AP supporting IEEE 802.11b through a 100 Mbps Ethernet crossover cable to a Dell Inspiron 8100 laptop with a 1 GHz Mobile Pentium III processor and 512 MB memory running Linux 2.4.7-10. The kernel has netfilter enabled to facilitate TCP-transparent receiver-side traffic control that are implemented as IP hook callback functions. We also performed benchmark experiments on a private IP-over-SONET testbed comprised of 9 Cisco 7206VXR routers—the wireline backbone segment—where the AP is directly connected to one of the routers and the PCs are connected to the other 8 routers acting as servers. The two set-ups yield similar results and we report benchmark suites from the laptop-to-AP wireline configuration. The BSS wireless segment is populated by 16 Compaq/HP 3800

and two 3600 series iPAQ pocket PCs with 64 MB memory running Familiar Linux v0.7.2. Figure 2(a) depicts some of the hardware components. Each pocket PC is housed in an external

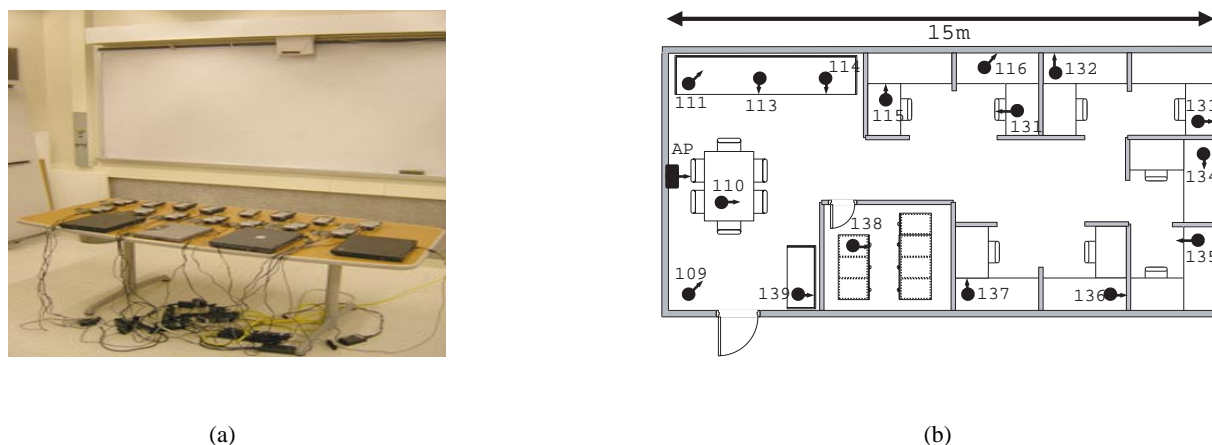


Fig. 2. (a) iPAQ pocket PCs and Enterasys RoamAbout R2 AP forming BSS. (b) Basement indoor office experiment environment showing locations of AP and wireless stations and their antennae direction.

PCMCIA jacket which connects an Enterasys RoamAbout 802.11b PC Card. The data rate on the AP and pocket PCs is set to 11 Mbps (fixed rate), RTS/CTS and power control are disabled, and the channel is fixed at an unoccupied frequency band with minimal cross-channel interference. We use WildPackets AiroPeek NX [1], a state-of-the-art commercial WLAN sniffing and analysis tool, to determine the state of the wireless medium for channel selection and monitoring of MAC-level transmission activity. The latter, in conjunction with tcpdump traces collected at the laptop and pocket PCs, is used to infer backlog Markov chain associated with TCP-over-WLAN dynamics. The experiments in this paper focus on an indoor office environment in the basement of the Computer Science Building at Purdue University. Figure 2(b) depicts the physical layout. We also performed benchmarks in a table top configuration where all pocket PCs are co-located on a conference table which minimizes the influence of distance on signal strength and resultant throughput.

C. Simulation Set-up

We use *ns* [3] with CMU's WLAN extension (version 2.27) to simulate the dumbbell wireless/wireline WLAN topology corresponding to Figure 1, where the IP network cloud is replaced by a single router. Wireline bandwidth is set to 100 Mbps, with link latency between router and

AP set to 1 msec and the link latency between wireline hosts and router set to 10 msec. The IEEE 802.11 BSS data rate is set at 11 Mbps and ACK frames are transmitted at 2 Mbps. Default channel noise is set at 10^{-6} BER (bit error rate). Other IEEE 802.11b related parameter specifications are summarized in Figure 3(a). An upper bound on the maximum achievable throughput by a single wireless station may be computed based on these parameters, which yields a frame completion time of $50 + T_{BO} + 192 + (224 + 8\ell)/11 + 10 + 192 + 112/2$ (μs) where ℓ is the frame payload size and T_{BO} is the length of the backoff interval. Figure 3(b) shows the components of a DCF frame transmission and acknowledgment schedule. Frame payload is

slot time	20 μs
SIFS	10 μs
DIFS	50 μs
CWmin	31
CWmax	1023
physical preamble	144 bits
physical header	48 bits
ACK frame	112 bits
MAC header + CRC	224 bits

(a)



(b)

Fig. 3. (a) IEEE 802.11b parameter specification. (b) DCF frame transmission and acknowledgment schedule.

transmitted at 11 Mbps and acknowledgment control frames are transmitted at 2 Mbps. The physical part (preamble + physical header) of both data and ACK frames is transmitted using 1 Mbps DBPSK modulation [4]. If the backoff interval is ignored, it takes about 1.25 msec to transmit a frame of size $\ell = 1000$ bytes, which implies a MAC throughput bound of 6.4 Mbps. The bound varies as a function of frame size ℓ . The theoretically expected single station throughput, considering the backoff counter, is 5.136 Mbps. The actual value obtained in simulation is 5.117 Mbps. In iPAQ experiments the single station measured throughput is 5.155 Mbps. Both agree well with the calculated value. When 2–4 wireless stations are present, the total throughput, despite collisions, can be higher than that of a single station due to a concurrent countdown effect of DCF with respect to backoff counters that leaves the channel less idle on average.

III. CHARACTERISTICS OF IEEE 802.11 DCF PERFORMANCE

A. DCF Throughput: Agility

The first issue concerns the throughput of DCF which has been claimed to degrade significantly as the contention level—offered load or number of stations—is increased. We start with simulation-based performance evaluation, then incorporate the impact of physical layer channel diversity and dynamic code rate shifting using experimentation.

1) *Equidistant DCF Throughput—Simulation:* We consider a BSS configuration where wireless nodes are symmetrically placed on a circle of radius 10 m with the AP located at the center. Equidistance and symmetry affect maximal DCF contention. Single point location—a logical configuration commonly used in contention-based MAC studies where all stations, including the AP, are co-located at a single point, random location, and other layout configurations are considered in Section III-A.3. Figure 4(a) shows simulated DCF throughput as a function of total offered load for 2–100 wireless stations where each station generates an equal share of the offered load. Individual offered load is constant bit rate traffic with a small uniformly random inter-packet noise (within 10% of the packet spacing interval) added to break up deterministic synchronization

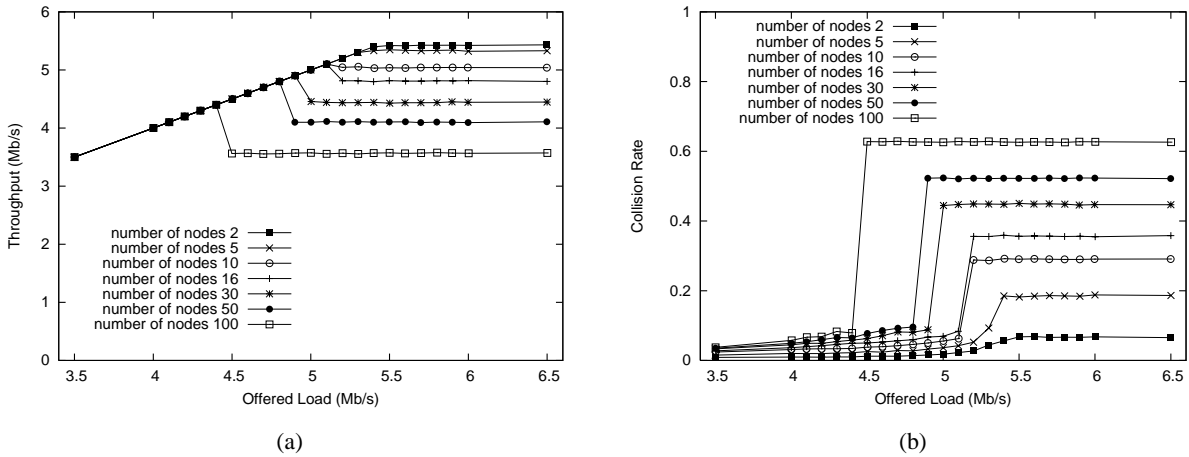


Fig. 4. (a) Simulated IEEE 802.11 DCF throughput as a function of offered load for 2–100 wireless stations. (b) Corresponding DCF collision rate.

effects. A single simulation run lasts for 200 seconds during which approximately 180,000 frame transmission events are generated with 10 wireless stations at saturation. Experiments also last for 200 seconds. We exclude the first 100 seconds from the reported performance measurements

to remove transient effects. First, we note that the 2 and 5 station throughput is higher than the single station throughput of 5.117 Mbps due to the concurrent countdown effect (cf. Section II-C). The single station throughput is not shown to reduce clutter. As offered load is increased, throughput grows linearly until a saturation point is reached at which throughput ceases to increase; in fact, it may decline. Onset of saturation throughput occurs after a critical offered load where the collision rate increases sharply as shown in Figure 4(b). When the number of stations is large, both peak and saturation throughput decrease and their relative gap widens. The drop in peak and saturation throughput as a function of the number of wireless stations is shown in Figure 5. Throughput decline is overall gradual with saturation throughput exhibiting a faster drop. At a moderate load of 16 wireless stations, peak throughput decreases 5.9% from the throughput level of 2 wireless stations and saturation throughput decreases by 11.4%. At a heavy load of 50 stations, the reductions are 11.4% and 24.2%, respectively. Peak throughput—

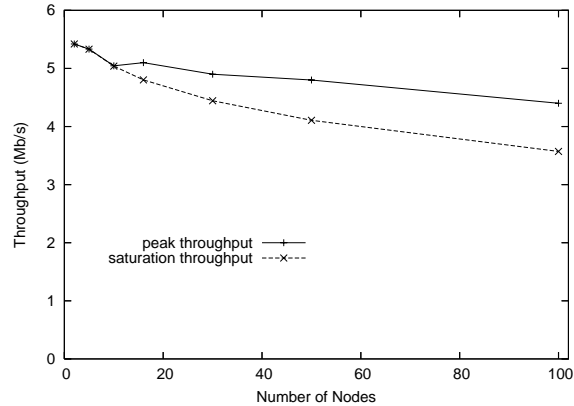


Fig. 5. Decrease in DCF peak and saturation throughput as the number of wireless stations is increased.

vis-à-vis saturation throughput—is relevant for two reasons. In [9] it is argued that saturation throughput should be considered as the attainable equilibrium performance measure. We find that when physical layer channel diversity is incorporated, the gap between peak and saturation throughput shrinks markedly, and when TCP operates over WLAN the joint actions of DCF and TCP feedback control drive the baseband channel near the peak throughput level. We discuss the first point next.

2) *Physical Layer Diversity—Experiment*: Physical layer channel diversity—a form of multiuser diversity [23], [39]—plays a significant role in mitigating DCF throughput degradation

under heavy contention. Figure 6(a) shows measured throughput of 802.11 DCF from experiments in the indoor office environment depicted in Figure 2(b). Offered load is increased from 4 Mbps to 7 Mbps with 2–16 iPAQ pocket PCs competing for the shared channel. UDP is used as the transport protocol. We observe two differences when compared to equidistant simulated DCF throughput in Figure 4(a): the overall throughput for 2, 5, 10 and 16 wireless stations is higher—in the range 5.7–5.876 Mbps for experiment vs. 4.816–5.432 Mbps for simulation—and the gap between peak and saturation throughput is much narrower. For 16 stations, the gap is

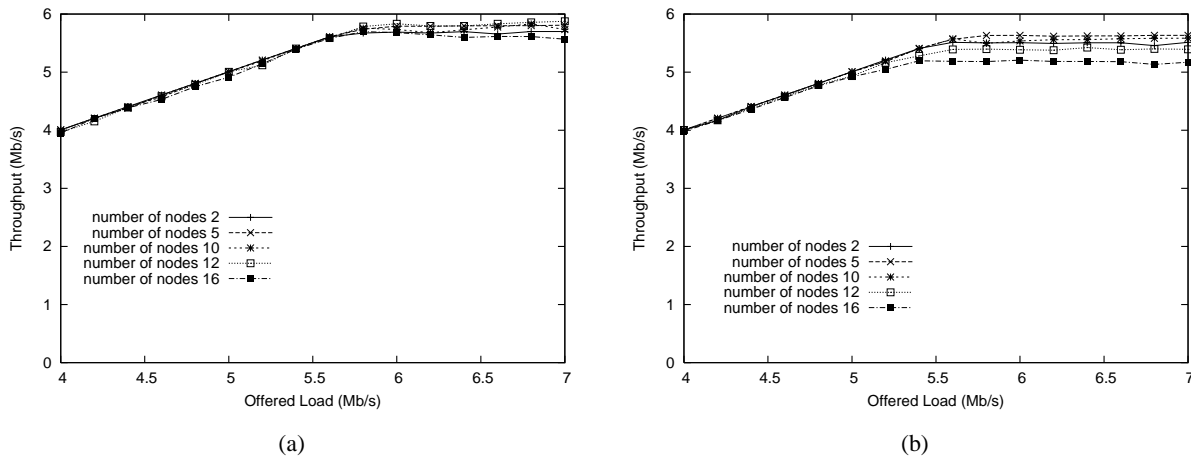


Fig. 6. (a) Empirical IEEE 802.11 DCF throughput as a function of offered load for 2, 5, 10, 12, 16 iPAQ pocket PCs in indoor office environment. (b) Corresponding DCF throughput in indoor table top environment.

5.9% in simulation versus essentially 0% in experiment. Figure 6(b) shows DCF throughput as a function of offered load from the indoor table top experiment. The less varied physical layer channel diversity resulting from close station proximity effects a smaller throughput gain vis-à-vis the indoor office configuration. Figure 7 compares the saturation throughput of DCF as the number of wireless stations is increased for the indoor office experiment, indoor table top experiment, and equidistant circle simulation. For 10 or 16 stations, we observe a 1 Mbps (20%) difference in achieved throughput between simulation and indoor office experiment, indicating the influence of physical layer diversity. When only a single wireless station is accessing the channel, saturation throughput—for both simulation and experiment—is in the 5.1–5.2 Mbps range.

In general, multiuser diversity may result from mobility and time-varying fading effects, and

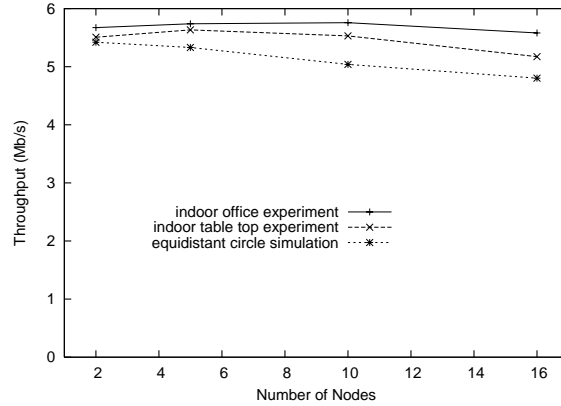


Fig. 7. Comparison of IEEE 802.11 DCF saturation throughput as a function of the number of wireless stations for indoor office experiment, indoor table top experiment, and equidistant circle simulation.

a scheduler that wishes to harness channel diversity for throughput maximization may try to allocate the channel at a given moment in time to an user with the best channel condition. In infrastructure WLAN hot spots where users, for the most part, change their location infrequently, physical layer channel diversity manifests in a persistent, location-dependent manner. That is, “advantaged” stations continue to be advantaged, and “disadvantaged” stations remain disadvantaged. Figure 8(a) shows the throughput share of 8 wireless stations under different offered loads in the indoor office environment. We observe that biases in channel diversity are preserved across different experiments which translates to corresponding biases in individual throughput share. The bias is location dependent—e.g., switching the pocket PCs makes little difference—

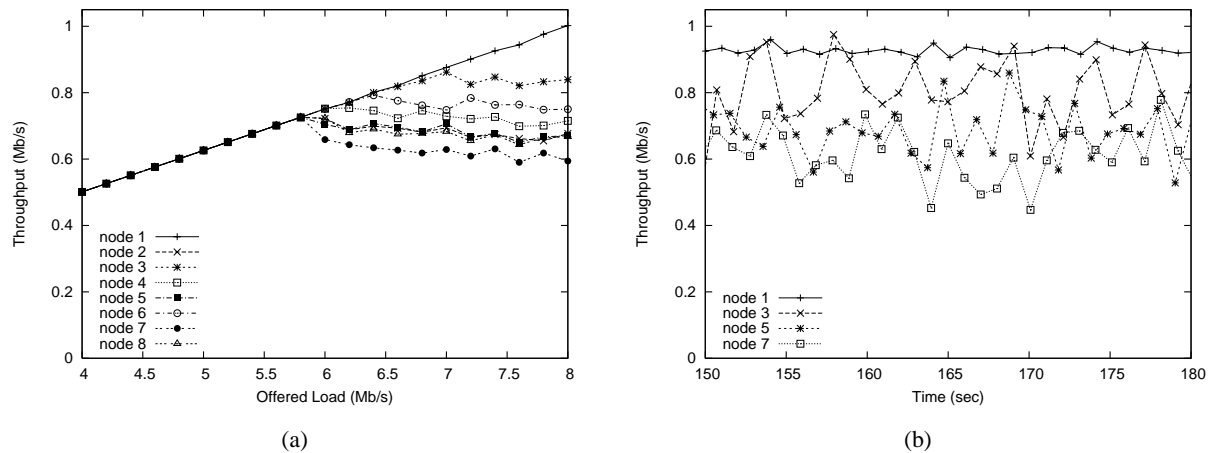


Fig. 8. (a) Persistent channel diversity and resultant stratification of throughput share in indoor office WLAN experiment with 8 iPAQ pocket PCs. (b) Persistent throughput stratification over time at offered load 7.4 Mbps for four nodes.

determined by the geometry of radio propagation in indoor environments. It is well-known that signal strength distribution in closed spaces is varied [14], [21], [38], whose theoretical foundation with respect to persistence, sensitivity, and high variability may be found in the chaotic nature of radio wave propagation in cavities [36]. DCF exploits this physical layer channel diversity in two ways: one, by a simple capture effect where a collision between two frames of different strengths may result in a successful decoding of the dominant frame due to signal strength differential, and two, by subsequent exponential backoff of the weaker station which amplifies the access priority that the stronger station receives. In Figure 8(a), we observe that as collision rate increases with increased offered load, the throughput share of the strongest station increases due to the reinforcing action of DCF. The DCF amplification effect is reminiscent of “the rich get richer and the poor get poorer” dynamics. From a system throughput perspective, because DCF “schedules” stations with stronger signal strength more frequently, system throughput improves by the maxim of multiuser diversity scheduling [15]. Figure 8(b), which shows throughput time dynamics of 4 of the 8 pocket PCs over a 30 second time window, indicates that persistent physical layer channel diversity also holds over time.

3) *Non-equidistant DCF Throughput—Simulation:* In the CMU wireless extension of *ns-2*, capture effect may be considered by an application of SIR (signal-to-interference ratio) thresholding. We consider four additional BSS configurations where distance-based capture effect may be isolated and discerned: “line” (configuration) where all stations are aligned 1 m apart on a line with the AP at one end, “near random” where stations are placed uniformly randomly inside a disk of radius 10 m with the AP at the center, “far random” where the AP is not at the center of the random disk but outside at a distance of 20 m from the center, and “single point” where all nodes, including the AP, are co-located at a single point. Figure 9 shows simulated DCF throughput as a function of the number of stations for the five configurations. We observe that the line configuration achieves the highest throughput, closely followed by the near random configuration. This is expected since channel diversity—due to path loss modeled by distance—is highest for the line configuration followed by the near random configuration. In the far random configuration, which is in distant fourth place, relative channel diversity inside the disk is dampened by the far distance of the wireless stations from the AP. The circle and

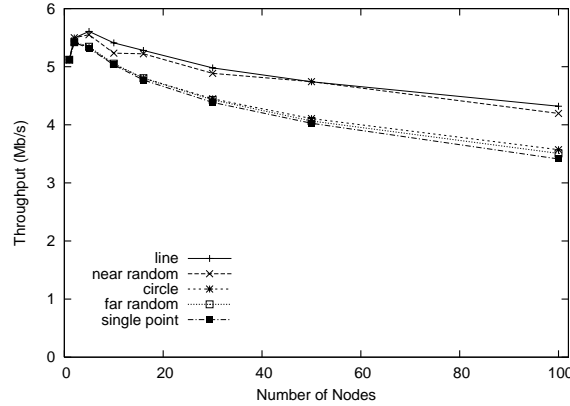


Fig. 9. Simulated DCF throughput as a function of the number of stations for line, near random, far random, single point, and circle configurations.

single point configurations achieve similar throughputs as the far random configuration due to their lack of diversity and resultant unbiased DCF multiple access competition.

4) *Dynamic Rate Shifting—Experiment:* In [41] it is shown that empirical IEEE 802.11b throughput in an infrastructure WLAN decreases from above 6 Mbps to below 2 Mbps as the number of stations is increased from 1 to 14. Perception of significant throughput degradation at moderate load is widespread, for example, in [19] it is claimed that “as the number of contending stations increases, aggregate capacity drops precipitously (to less than 1 Mb/s with 10 contending stations)” which is attributed to the multiple access nature of IEEE 802.11 CSMA/CA. We do not doubt the validity of the empirical observations—we believe they are factually accurate—but we question the conclusions drawn from the observations, in particular, the assignment of responsibility to DCF.

Figure 10 shows IEEE 802.11 DCF throughput as a function of the number of stations from an indoor table top experiment for different data rates of 802.11b—11 Mbps, 5.5 Mbps, 2 Mbps and 1 Mbps—and dynamic rate shifting (“auto rate”) implemented in Enterasys WLAN cards. At fixed data rates, the throughput curves are relatively flat as the number of pocket PCs is increased from 2 to 18, consistent with the graded throughput behavior seen in Figure 7. When auto rate is enabled—the default mode in most WLAN cards—aggregate throughput declines drastically as seen in Figure 10, dropping below 1 Mbps at 15 wireless stations. The prominent throughput decline, however, is not due to DCF. Testing of several 802.11b vendor cards with AiroPeek NX [1] monitoring MAC transmission activity reveals that the dynamic rate shifting algorithms

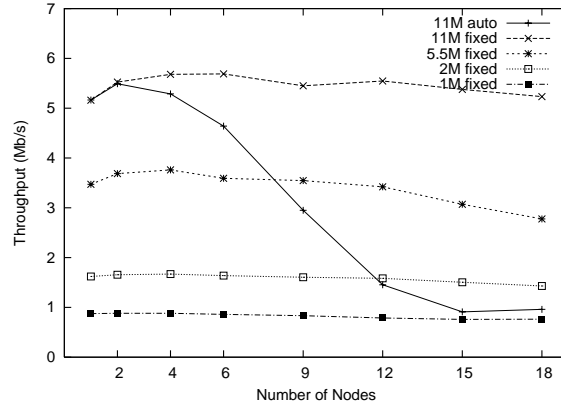


Fig. 10. Empirical IEEE 802.11 DCF throughput as a function of the number of pocket PCs for auto rate and fixed data rates 11 Mbps, 5.5 Mbps, 2 Mbps and 1 Mbps in indoor table top environment.

implemented in WLAN cards—most are realized in firmware—have difficulty distinguishing collision from channel noise. For example, in the Enterasys RoamAbout 802.11 DS High Rate card (Orinoco chipset), down shifting is triggered by 2 consecutive failures to receive an 802.11 ACK frame. When an ACK control frame is not forthcoming, the sender cannot determine if the corresponding 802.11 data frame was corrupted by channel noise or collision. The rudimentary nature of vendor-specific dynamic rate shifting schemes—rate control is not part of the IEEE 802.11 standard—has the detrimental effect of significantly reducing throughput under moderate contention, even when channel noise is small. TCP exerts an interesting mitigating effect on throughput degradation under dynamic rate shifting which is discussed in Section IV-D.

5) *VBR Traffic and Channel Noise—Simulation:* The benchmark results are robust in the sense that variations in the set-up such as variable bit rate (VBR) input traffic—as opposed to constant bit rate (CBR) traffic—and BER do not fundamentally affect the conclusions. Figure 11(a) shows peak and saturation WLAN throughput as a function of the number of wireless stations when traffic impinging on the MAC layer is Poisson. We observe that saturation throughput of Poisson input coincides with that of CBR input. Peak throughput exhibits a small gap—3.2% for 16 nodes—that stems from the more bursty nature of Poisson input which leads to periods of higher and lower contention, neither of which is conducive to improved DCF throughput. A more realistic workload in the form of heavy-tailed file sizes for TCP-over-WLAN traffic is considered in Section IV-E. Figure 11(b) shows peak and saturation DCF throughput as a function of BER for 16 wireless stations in the equidistant circle configuration. We observe a

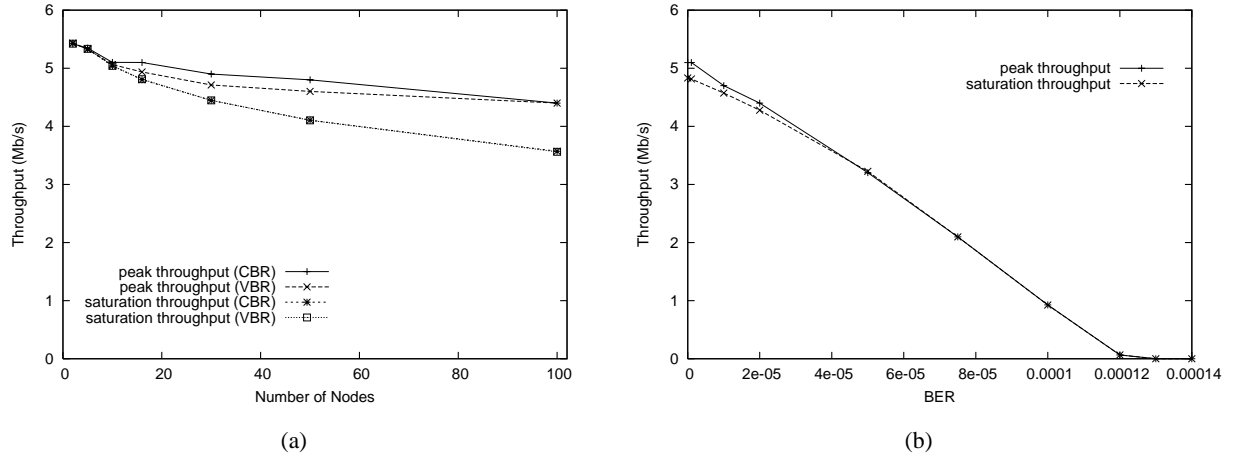


Fig. 11. (a) Peak throughput and saturation throughput for CBR and Poisson VBR input traffic. (b) Peak and saturation throughput as a function of BER for 16 wireless stations.

near-linear decline in throughput as BER is increased from 10^{-6} —a typical indoor noise level [2], [18]—to 0.00012, a two orders of magnitude increase. Peak and saturation throughput merge for large BER where frame errors from channel noise dominate their counterpart from collision. A discussion of BER’s influence on throughput may be found in [13].

B. DCF Fairness and Jitter

In this section, we discuss the sensitive dependence of DCF fairness and jitter on offered load, and issues related to its control.

1) *DCF Fairness—Diversity Amplification*: Figure 12 shows fairness, presented as the ratio of minimum throughput over maximum throughput across participating stations, as a function of offered load for 2–100 stations in the equidistant circle configuration simulation. We observe a sharp degradation of fairness at a critical offered load commensurate with a sharp increase in the collision rate (cf. Figure 4(b)). Unlike throughput, which is mitigated by physical layer channel diversity, unfairness is further amplified by DCF. This is discernible on a per-flow basis in Figure 13(a) where the individual throughput share of 16 wireless stations in a line configuration is shown as a function of offered load. Up to the critical offered load, throughput share is overall equitable. After the critical load where collision rate sharply increases, individual throughput share stratifies into persistent levels whose total width—the minimum throughput

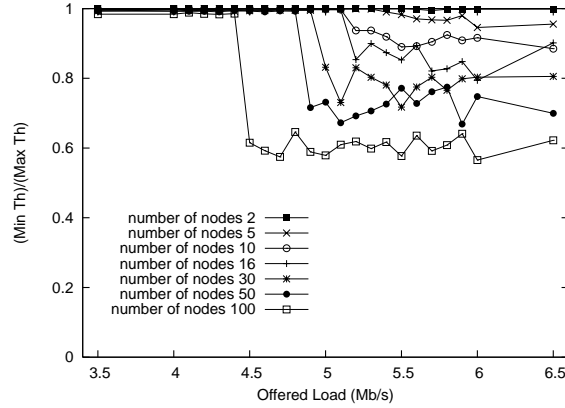


Fig. 12. Simulated DCF fairness as a function of offered load for 2–100 wireless stations in equidistant circle configuration.

over maximum throughput ratio—continues to expand. DCF exerts a self-reinforcing “the rich get richer the poor get poorer” effect that amplifies unfairness triggered by multiuser diversity. In the line configuration, multiuser diversity stems from SIR capture effect that puts distant stations at a competitive disadvantage. Figure 13(b), which plots the corresponding throughput share of 16 wireless stations in the equidistant circle configuration, shows that when persistent multiuser diversity is removed, so is DCF’s diversity amplification effect.

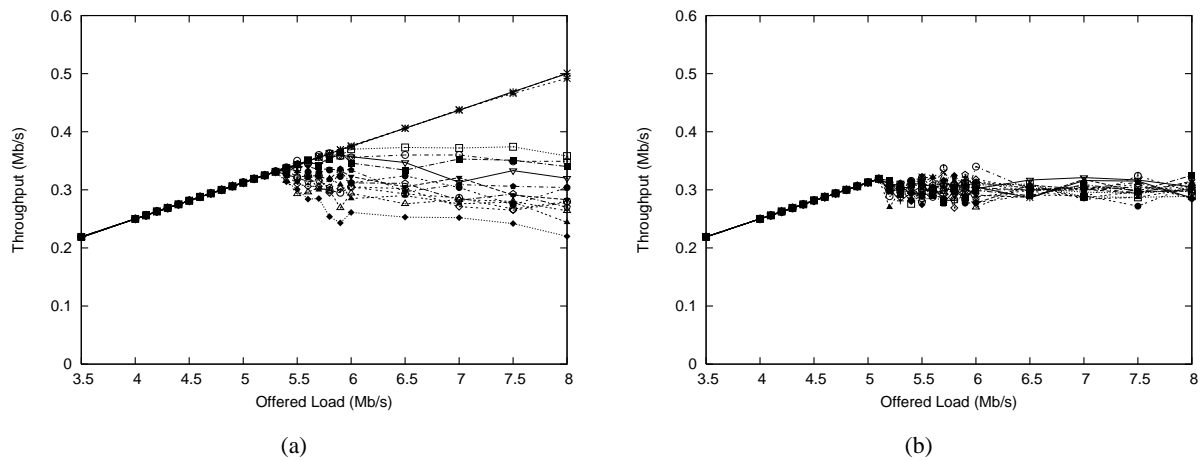


Fig. 13. (a) Simulated DCF fairness with respect to individual throughput share as a function of offered load for 16 wireless stations in line configuration. (b) Corresponding DCF fairness plots in equidistant circle configuration.

2) *DCF Jitter—Sensitivity*: We consider jitter performance—in the sense of throughput variation over time—at different offered loads. We use normalized standard deviation to capture throughput variability in time. Figure 14(a) shows normalized standard deviation as a function

of offered load for 2–100 stations in the equidistant circle configuration. We observe that at the critical load where collision rate sharply increases (and fairness sharply degrades), jitter exhibits

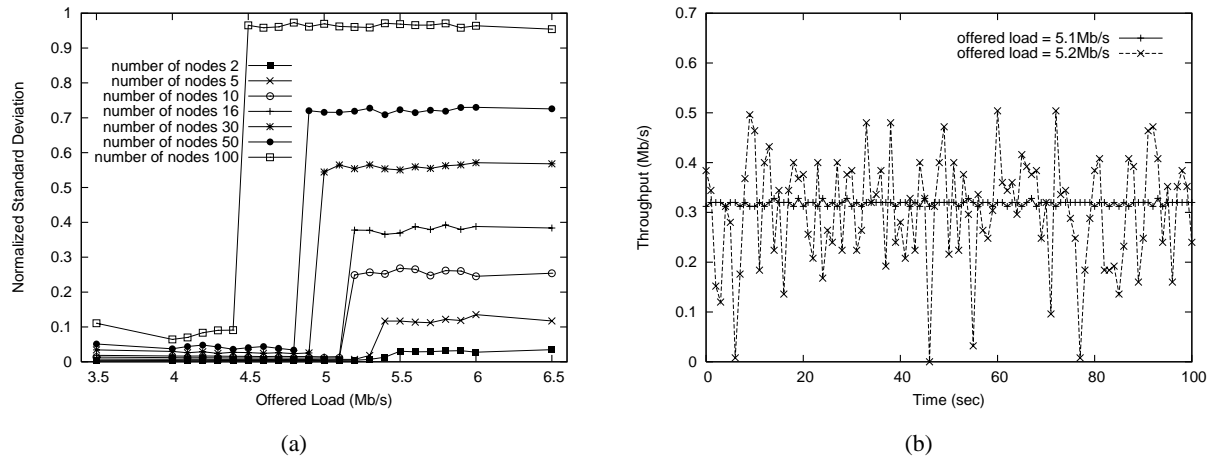


Fig. 14. (a) Simulated DCF jitter performance—captured as normalized standard deviation of throughput—for the equidistant circle configuration. (b) Throughput variation over time before (5.1 Mbps) and after (5.2 Mbps) critical offered load.

a sudden jump. Operating an infrastructure WLAN in the saturation regime need not degrade throughput, however, it markedly increases throughput variability which has bearing on VoIP (voice-over-IP) and multimedia streaming applications. Figure 14(b) shows throughput variation over time for a wireless station—there are a total of 16 nodes—when offered load is slightly below (5.1 Mbps) the critical offered load and when it is slightly larger (5.2 Mbps). Second-order throughput and delay performance experiences a phase transition at the critical offered load.

3) *Link Layer Rate Control*: In [20], [44] link layer rate control is proposed to mitigate CSMA/CA throughput decline under excessive offered load. Our results show that unless the number of wireless stations in a BSS is very large, DCF throughput degrades gracefully, aided by DCF’s ability to exploit physical layer channel diversity. Fairness and jitter, however, suffer significantly under excessive offered load, and rate controls that limit traffic impinging on the 802.11 MAC can improve fairness and jitter. Viewing the “dome shaped” static input-output profile of IEEE 802.11 DCF (cf. Figure 4(a)) as a dynamic feedback control problem, it is not difficult to design a PI controller that is asymptotically stable and efficient. The well-known instability problem of ALOHA (and ALOHA-like) contention-based protocols [22], [34] applies only in the queuing sense—backlog growing unboundedly if the application layer arrival rate

exceeds the link layer service rate—but not for maximizing the link layer’s throughput which is a function of the controlled link layer arrival rate. For open-loop applications such as VoIP link layer rate shaping may be harmful. With IEEE 802.11e support, prioritized MAC access may be affected using EDCF which significantly reduces jitter. Figure 15 shows MAC throughput over time in the saturation regime for high- and normal-priority traffic under 802.11e. For closed-

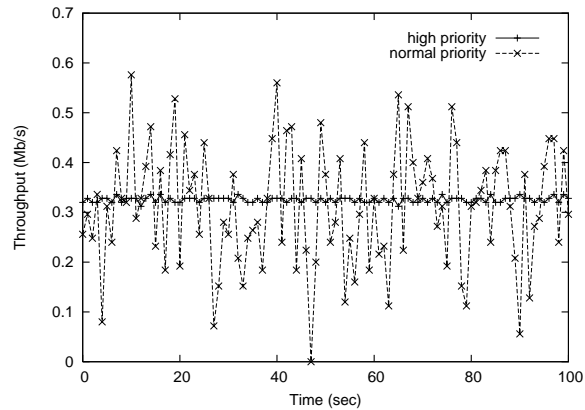


Fig. 15. Throughput variability in time under IEEE 802.11e EDCF for high- and normal-priority traffic under saturation.

loop or elastic applications such as TCP-based file transfer—the dominant constituent of Internet traffic which has also been confirmed for WLANs [7], [25]—link layer rate control may be beneficial, especially due to the increased collision rate associated with the saturation regime (cf. Figure 4(b)) that may translate to increased frame error rate. We established in Section III-A.4 that dynamic rate shifting implemented in WLAN cards easily confuse collision with channel noise leading to significant throughput degradation. In the case of TCP which is sensitive to spurious packet loss this may prove to be problematic. Interestingly TCP-over-WLAN performance does not suffer under this problem, achieving performance on par with wireline TCP. The reasons underlying this surprising agility is the subject of the next section.

IV. TCP-OVER-WLAN PERFORMANCE

We first discuss throughput performance of TCP-over-WLAN, followed by explication of its prowess, and benchmarking of receiver-side traffic controls aimed at improving fairness/jitter. The latter is relevant when TCP coexists with VoIP. We use simulation to study the details of TCP-over-WLAN dynamics augmented by experimental benchmarks.

A. Scalable Throughput

It is known from steady-state TCP analysis [31] that TCP throughput depends polynomially on packet loss rate (i.e., $\propto p^{-1/2}$) which renders TCP sensitive to spurious packet loss. An important focus of past TCP-over-Wireless research [8], [33] has been distinguishing channel noise from congestion, so that TCP's congestion control may be desensitized against random packet loss. Pronounced collision, a form of congestion on the wireless segment, can in indoor environments dominate channel noise—the reason why WLAN throughput, under the action of dynamic rate shifting, drastically degrades when subject to moderate contention (cf. Figure 10)—and significantly diminish TCP throughput. To evaluate TCP-over-WLAN performance under multiple access contention, we use the single point simulation configuration which suffers under the heaviest collision and throughput drop, providing maximal challenge to TCP. We consider a client/server environment where wireless stations, acting as clients, fetch files from wireline servers. This incorporates the TCP data/ack collision problem [17], [42]. We use TCP NewReno without selective and delayed ACK, and study infinite source sessions in steady-state. TCP sessions with heavy-tailed file transfers are considered separately. Figure 16(a) shows TCP throughput as a function of the number of wireless stations. As multiple access contention is increased from 1 to 100, TCP-over-WLAN throughput remains flat. The same goes for TCP ACK traffic which is at the same packet rate (pps) but smaller data rate (bps). In contrast, UDP

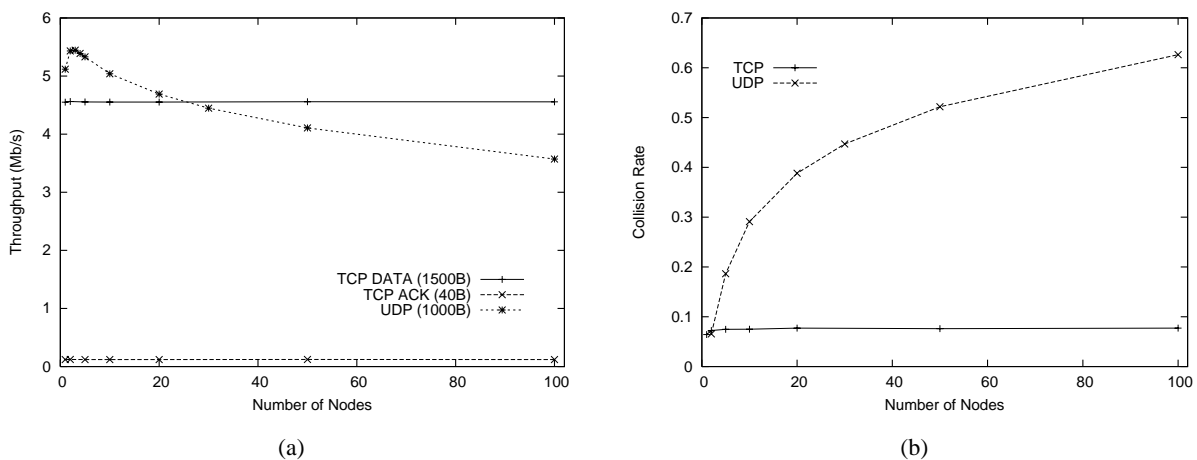


Fig. 16. (a) TCP-over-WLAN throughput and ACK traffic as a function of the number of wireless stations; UDP throughput is shown for comparative purposes. (b) Corresponding collision rate.

(i.e., DCF) throughput declines under high contention. Figure 16(b) shows the corresponding collision rate experienced by TCP data and ACK frames at the DCF MAC layer which also remains essentially flat. We use a MSS of 1500 bytes for the above benchmarks but the same qualitative profile holds for other frame sizes. The AP has a buffer size of 200 (in frame units), a capacity in the same range as the Enterasys RoamAbout R2 AP.

Figure 17 shows frame error rate, collision rate, channel error rate (FER + collision rate), frame discard rate, and AP buffer drop rate as the number of contending stations is increased. At the given BER level 10^{-6} , common for indoor environments [2], [18], collisions make up the bulk of frame errors. However, no frames are discarded by the 802.11 MAC layer due to DCF's ARQ which performs 7 retransmissions under exponential backoff before giving up. The loss rate at the AP shows that it is downstream buffer overflow at the AP—a classical wireline bottleneck that exists in other pure wireline contexts such as low bandwidth access links [35]—that throttles the application layer data rate. The flat TCP throughput curve is caused by the flat

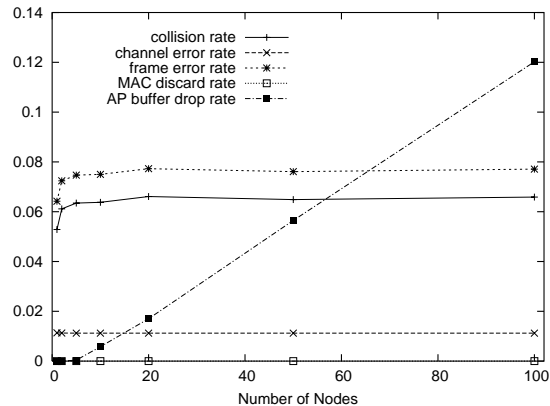


Fig. 17. Frame error rate, collision rate, channel error rate, frame discard rate, and AP buffer drop rate as a function of the number of stations.

WLAN collision rate. Collision rate stays flat even if the AP is endowed with infinite buffer capacity. TCP-over-WLAN is able to operate at a small, constant collision rate independent of the number of TCP flows competing for the shared wireless baseband bandwidth. We refer to this as TCP-over-WLAN's scalable throughput property. The TCP data/ack collision problem raised in [17], [42] does not materialize. In Section IV-C we explicate how the scalable throughput property comes about.

B. Efficiency: UDP Emulation

To evaluate how efficiently TCP utilizes WLAN capacity, we emulate TCP using UDP in a rate-matched, open-loop fashion where n downstream UDP sessions transmit 1500 byte data frames at λ pps that is matched by n upstream UDP flows transmitting 40 byte packets (mimicking ACK packets) at the same rate. From Section III we know that under excessive offered load collision increases sharply and DCF throughput declines, albeit gradually. Our aim is to understand at what offered load TCP drives DCF which determines channel utilization and capacity. Figure 18

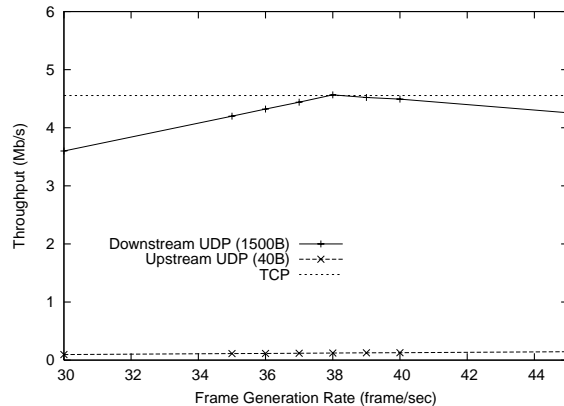


Fig. 18. UDP emulation of TCP with 10 wireless stations with varying frame generation rate λ .

shows downstream and upstream UDP throughput as the frame generation rate λ is varied. We also show the throughput attained by TCP under the same benchmark setting. We observe that UDP throughput increases with increased offered load until it hits a peak—coinciding with TCP’s throughput—after which it declines due to increased collision. The UDP emulation result shows that when the AP-to-wireless station traffic ratio (in pps) is $n : 1$, a typical scenario for WLAN hot spots that are used as Internet access networks, TCP is able to drive DCF at its maximal throughput level. In other words, TCP-over-WLAN operates the WLAN at its peak throughput.

C. TCP-over-WLAN Dynamics: Effective Contention

1) *Markov Chain Analysis—Negative Drift*: Our goal is to understand how TCP-over-WLAN is able to achieve a constant collision rate over a wide contention range of 1–100 wireless stations. We define a Markov chain that tracks TCP-over-WLAN dynamics at the WLAN level: at any instant in time, the state of the birth-death Markov chain is given by the number of backlogged

wireless stations, including the AP, where backlogged means that the MAC protocol—typically implemented as firmware in NICs—has received one or more frames from the upper layer that have not been successfully transmitted yet. Thus the backlog chain counts the number of actually active stations participating in the multiple access competition at an instant in time. In simulation, it is straightforward to infer the backlog Markov chain from measurement logs: starting from time 0, we have a point process whose realization or sample path we track. Conditioned on these states, we tabulate next state transition statistics from which the transition rates can be estimated. Figure 19 shows the backlog Markov chain inferred from a single point configuration simulation with 20 wireless stations. Starting from “counting” state 3, we see a strong negative

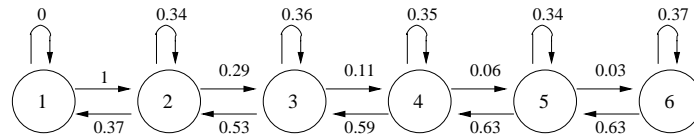


Fig. 19. TCP-over-WLAN dynamics: inferred backlog Markov chain from simulation benchmark with 20 wireless stations.

drift—rate 0.53 to state 2 versus rate 0.11 to state 4—that ends at state 6. In the client/server wireless/wireline TCP environment, the AP is a conduit for all downstream traffic from wireline servers to wireless clients, and vice versa for the resultant upstream ACK traffic. When the AP successfully grabs the shared channel, it may send a TCP data frame to a wireless station with an existing backlog—in which case the counting state remains put (i.e., a self-loop)—or the AP may send it to a non-backlogged station in which case the counting state increases by 1. The full Markov chain contains micro-states that count the number of backlogged packets per station. The chain shown in Figure 19 is a projection of the full chain. A client station, upon grabbing the channel, may have more than one frame in its backlog, in which case the counting state stays put; otherwise, it is decremented by 1.

DCF’s contribution to the negative drift is as follows: the AP in a BSS, by virtue of its conduit role with a $n : 1$ traffic ratio, is in a special forwarding position. However, under DCF all wireless stations, including the AP, are treated equal with respect to channel access. For the counting chain to grow, it requires that the AP transmit a TCP data frame. But the larger the counting state k , the smaller the probability ($\approx 1/k$) that the AP will win in the channel grabbing competition. Conversely, the larger the likelihood ($\approx 1 - 1/k$) that one of the wireless stations

will win the competition. Hence the strong negative drift that pulls the Markov chain toward the origin. Figure 20(a) shows the equilibrium probability distribution of the Markov chain. Figure 20(b) shows a typical sample path of TCP-over-WLAN dynamics over the state-space of backlogged stations. Figure 21 shows the average, maximum, and average plus two standard

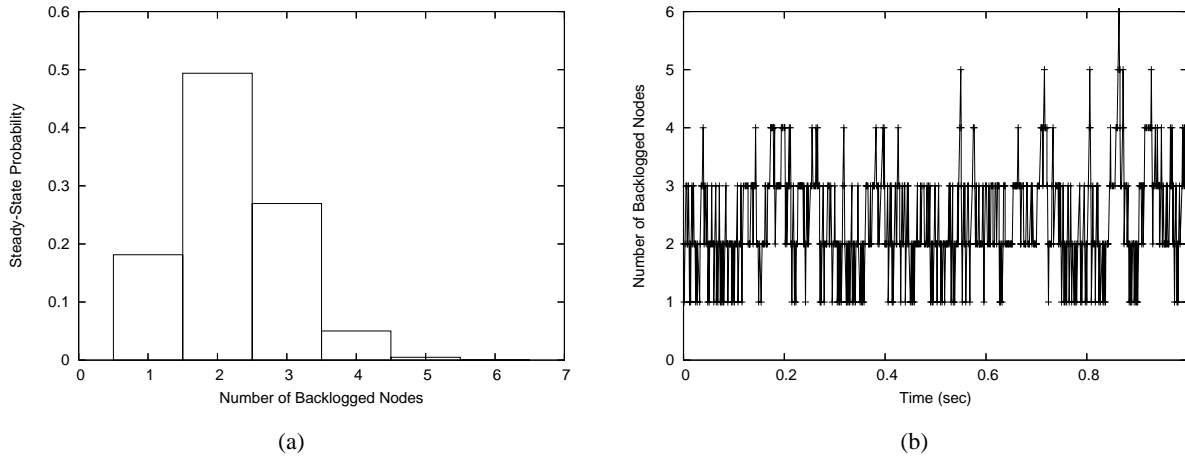


Fig. 20. (a) Equilibrium probability distribution of backlog Markov chain with 20 wireless stations. (b) Sample path of TCP-over-WLAN dynamics over the state-space of backlogged stations.

deviations counting states, in equilibrium, of all backlog Markov chains for 1–100 stations in the simulation benchmarks of Figure 16. The average counting state is 2.2, even when there are 100 contending wireless stations. This implies that the WLAN operates under an effective contention level of 2–3 wireless stations. 95% of all data points fall within two standard deviations of the mean which, in Figure 21, is around 4 active stations. The maximum is 7 active stations which are reached less than 5% of the time. Pertinent WLAN performance measures such as MAC throughput and collision rate also correspond to that of 2–3 wireless stations, albeit in saturation mode. The throughput and collision rate for 2 wireless stations may be discerned in Figure 4. Overall it is desirable to operate a WLAN at an effective contention level of 2–3 wireless stations, even in saturation mode.

2) *Verification through Experiment:* Simulation is well-suited for carrying out accurate backlog Markov chain analysis because all relevant events can be logged with certainty and there is a global clock that makes event synchronization simple. In experimental benchmarking, there is system noise and synchronization of events, given only local clocks, is an inherent technical

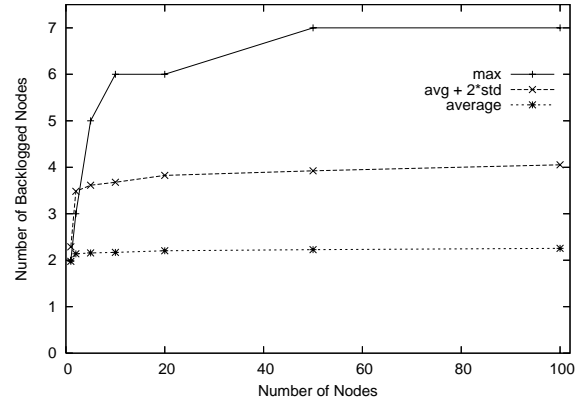


Fig. 21. Average counting state in equilibrium for 1–100 wireless station simulation benchmark.

problem. With the aid of AiroPeek NX, a state-of-the-art commercial WLAN sniffing and analysis tool, and tcpdump logging at the laptop and all pocket PCs, we are able to estimate the backlog Markov chain using sequential event ordering at the AiroPeek sniffer. This method works but with a caveat: due to channel noise, collision, and system noise, not all frame transmission events are sensed by the sniffer. This leads to ambiguity and resultant frames that cannot be resolved. The fraction of such frames, however, is less than 2%, and we estimate the backlog chain after excluding these frames. Figure 22 shows the inferred Markov chain from a table top experiment with 15 pocket PCs. The average counting state is 2.59—a little higher than that of simulation-based benchmark results—which we attribute to the aforementioned inaccuracies. A strong negative drift is discernible consistent with backlog Markov chain analysis.

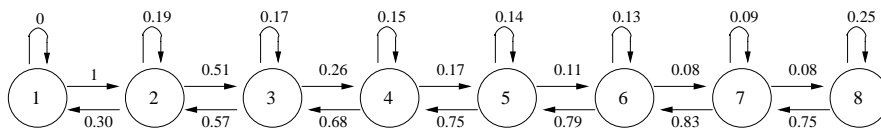


Fig. 22. Backlog Markov chain inferred from table top client/server TCP benchmark experiment with 15 iPAQ pocket PCs.

3) *DCF vs. TCP Feedback Control Contribution to Negative Drift*: Both DCF and TCP feedback control contribute to the strong negative drift in the backlog Markov chain, with DCF being the dominant factor. Figure 23 shows the average and average plus two standard deviation counting states of open-loop UDP emulation of TCP with a $n : 1$ AP-to-wireless client traffic ratio for 5–100 wireless stations. For a given number of wireless stations, the traffic rate λ is set at a value that achieves peak throughput (cf. Figure 18). It turns out that the relation

$n\lambda = 380$ fps holds for peak throughput. Figure 23 also shows the counting states for TCP for comparative purposes. The average counting state of UDP emulation is in the 2–3 range, closer

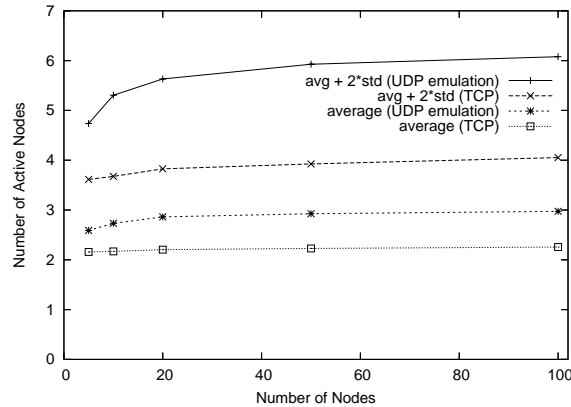


Fig. 23. Average counting state of UDP emulation for 5–100 wireless stations.

to 3, whereas in the case of TCP it is closer to 2. We observe the characteristic flatness of the effective contention level as the number of wireless stations is increased from 5 to 100. Since UDP emulation is open-loop, TCP’s self-clocking feedback mechanism doesn’t enter into play, and it is DCF’s self regulating mechanism (cf. Section IV-C.1) along with the $n : 1$ traffic ratio characteristic of hot spot infrastructure WLANs that leads to scalable performance. The average plus two standard deviation curve lies in the 5–6 counting stage range, somewhat higher than the 3–4 range for TCP. Qualitatively the scalable throughput property is achieved by DCF alone, although quantitatively the counting states are a little higher without TCP running on top of DCF. It is in the latter that TCP’s self-clocking feedback mechanism additionally contributes to negative drift in the backlog chain.

D. Dynamic Rate Shifting under TCP-over-WLAN

In Section III-A.4 we showed that dynamic rate shifting implemented in WLAN cards easily confuse collision with channel noise resulting in significant throughput degradation even under moderate load when channel conditions are good. Figure 24 shows empirical TCP throughput in the indoor office environment for auto rate and fixed rates 11, 5.5, 2, and 1 Mbps as the number of contending iPAQ pocket PCs is increased from 1 to 14. Unlike in Figure 10, we observe a flat throughput curve under auto rate that is facilitated by the $n : 1$ traffic ratio of hot spot WLANs and the mitigating influence of TCP’s self-clocking mechanism. TCP-over-WLAN, by

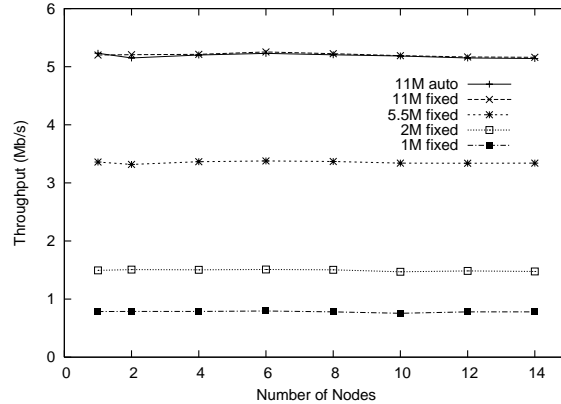


Fig. 24. Empirical TCP throughput as a function of the number of pocket PCs for auto rate and fixed data rates 11 Mbps, 5.5 Mbps, 2 Mbps and 1 Mbps in indoor office environment.

operating the shared baseband channel at an effective contention level of 2–3 wireless stations, is able to keep the collision rate in check preventing frequent occurrence of two consecutive missing 802.11 ACK frames that trigger downshifting to fallback rates. With 14 pocket PCs, less than 0.5% of IEEE 802.11 data frames carrying TCP payload are transmitted at fallback rate 5.5 Mbps (or below) under dynamic rate shifting—data frames with 2 and 1 Mbps data rates are essentially nonexistent—whose low occurrence stems from the fact that less than 0.1% of 802.11 ACK frames are missing back-to-back. The higher fraction (0.5%) of data frames transmitted at fallback rates is due to an asymmetry in the downshift/upshift procedure: upshift in data rate is instituted more conservatively than downshift. Nonetheless, their low frequency renders their performance impact negligible.

E. Heavy-Tailed File Sizes

TCP file transfer constitutes the bulk of Internet traffic and file sizes tend to be heavy-tailed [32] which has also been noted for WLANs [7], [25]. We consider on/off TCP file transfer workload with exponential session interarrival time—mean 20 msec—and heavy-tailed files modeled by a Pareto distribution with tail index 1.3 and location parameter 1000. The simulation was run for 1000 seconds to allow for the sample mean to converge to the population mean, a process significantly slower than with light-tailed distributions. The population and sample means were 4.333 and 4.281 (in packet units), respectively. Figure 25(a) shows TCP throughput under heavy-tailed and infinite source workloads as the number of wireless stations is increased. For the

given session interarrival time, it requires 20 stations to offer sufficient load and reach maximum throughput. The 500 Kbps gap with infinite source TCP stems from the overhead associated with frequent connection set-up and tear-down of short-lived TCP sessions which make up the majority

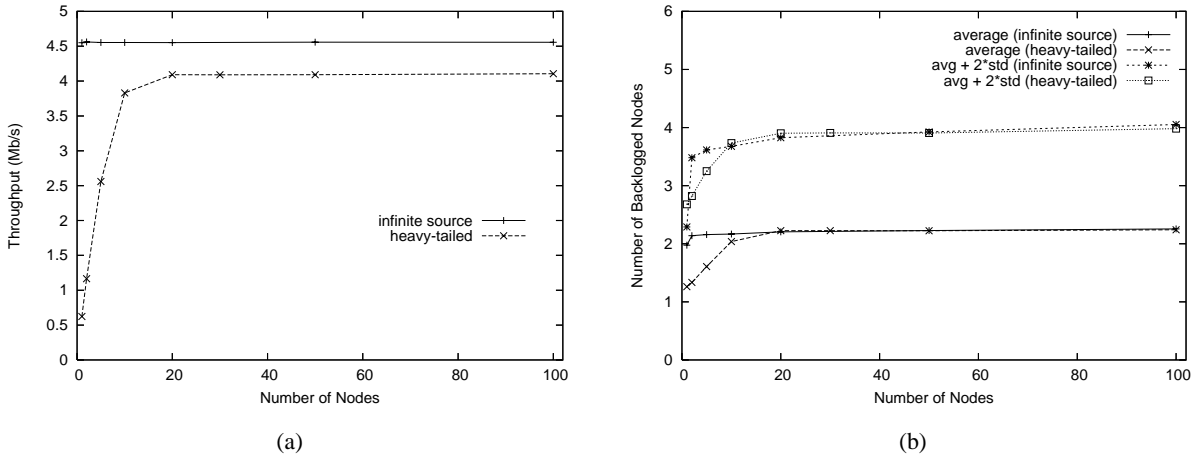


Fig. 25. (a) TCP throughput with Pareto file size distribution vs. infinite source as a function of number of wireless stations. (b) Corresponding comparison of average and average plus two standard deviation counting states.

of TCP sessions. Figure 25(b) shows the corresponding backlogged station plot for average and average plus two standard deviation counting states. When offered load is sufficiently high, we find close agreement between heavy-tailed and infinite source workload with respect to effective contention level. The throughput curve is flat thereafter, showing the scalable throughput property of TCP-over-WLAN in the presence of bursty workload.

F. TCP-over-WLAN Mitigation: Persistent Unfairness

In Sections III-A.2 and III-B.1 we showed that physical layer diversity in conjunction with DCF's diversity amplification effect leads to persistent unfairness across both space and time. Persistent unfairness is a characteristic trait of WLANs and different from transient unfairness stemming from AP buffer overflow. The latter predominantly affects short-lived flows, the very flows where a 200% slowdown—e.g., file transfer completion time increased from 1 to 3 seconds—does not mean as much QoS perception-wise as a slowdown from 5 to 15 minutes for long-lived connections. In the preceding sections, we demonstrated the mitigating influence of TCP-over-WLAN with respect to throughput, including a neutralizing effect on dynamic rate

shifting which easily confuses collision with channel noise. Figure 26 shows the mitigating influence of TCP-over-WLAN with respect to persistent unfairness for 14 pocket PCs in the indoor office environment. Without TCP, WLAN throughput exhibits significant variation among

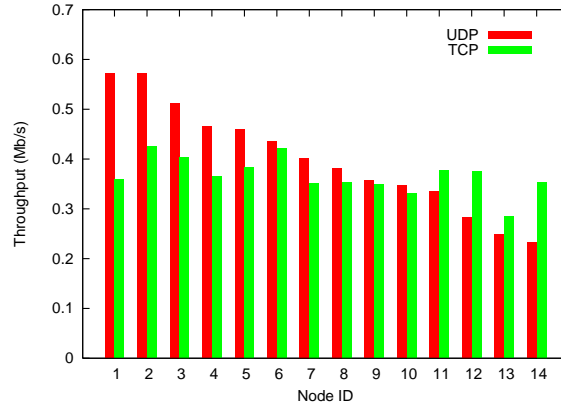


Fig. 26. The mitigating influence of TCP-over-WLAN on persistent unfairness for 14 iPAQ pocket PCs in indoor office environment.

the 14 wireless stations caused by physical layer channel diversity. Throughput share is distributed evenly across the range 232–572 Kbps with a min/max ratio of 0.41. With TCP, unfairness is markedly reduced where stations who were receiving an excessive share get their throughput reduced, and vice versa for stations in disadvantaged locations. The mitigating influence of TCP-over-WLAN encompasses both throughput and fairness.

G. Receiver-Side Traffic Control

TCP-over-WLAN achieves scalable throughput by operating DCF at an effective contention level of 2–3 wireless stations, albeit in the saturation regime. Reduced contention also helps alleviate persistent unfairness. The collision rate for 2–3 stations in saturation is not sufficiently large to cause IP datagram loss on the WLAN segment due to DCF’s ARQ, although it may increase jitter that can adversely influence other flows sharing the wireless medium such as VoIP. The dominant contributor of jitter is buffer overflow at the AP (cf. Figure 17) due to a classical wireline bandwidth mismatch problem. If priority queuing at the AP and prioritized channel access—both part of IEEE 802.11e—is supported, then jitter for high priority flows can be kept in check (cf. Figure 15 in Section III-B.3). An alternative approach to jitter control that is legacy system compatible is receiver-side traffic control proposed in [35] for improving TCP

performance over low bandwidth wireline access links. By adjusting the advertised window in the network/link layer of the protocol stack at end systems—transparent to TCP and application—it is possible to throttle traffic rate to prevent buffer overflow and excessive queuing¹. In Linux, transparent receiver-side TCP traffic control can be implemented using a dynamically loadable module that registers callback functions with IP hooks in netfilter—a kernel facility that extends IP chains—available in Linux 2.4+. In Windows, transparent receiver-side control can be realized as an intermediate driver in NDIS. We have implemented receiver-side advertised window control and virtual delay control—a complement to advertised window control that delays ACK transmission at receiver-side to emulate elongated round-trip time (RTT) to pace the sender’s data rate—as netfilter modules in Linux.

Figure 27(a) shows TCP throughput variation over time for 10 pocket PCs in the indoor office environment without receiver-side traffic control. We observe significant fluctuations resulting from buffer overflow at the downstream AP buffer to which TCP congestion control reacts. Figure 27(b) shows TCP throughput dynamics for the same set-up when receiver-side advertised window control is enabled. In this benchmark, advertised windows are set to 5. Throughput fluctuation is quiescent and jitter control is achieved without sacrificing system throughput:

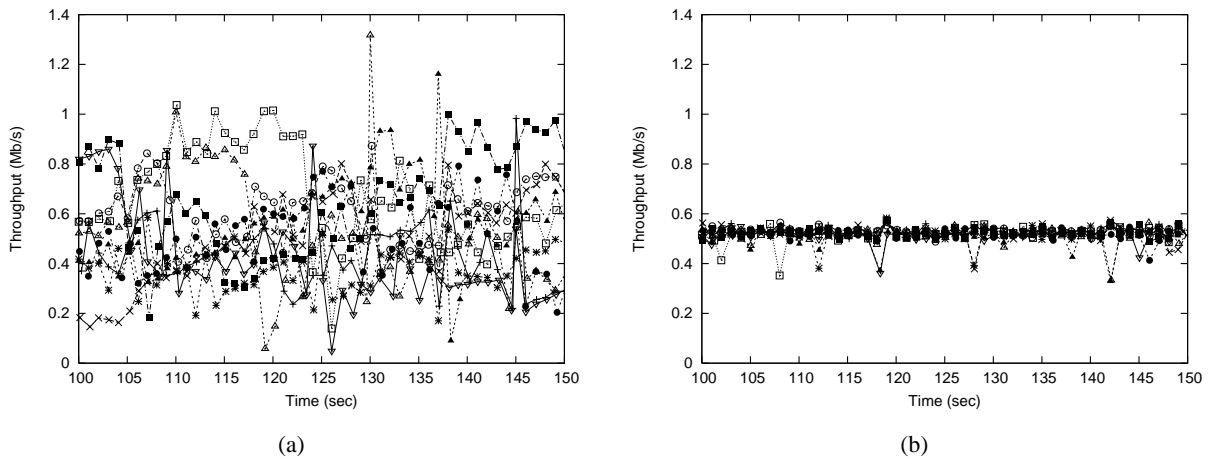


Fig. 27. (a) Jitter with respect to throughput variation experienced by 10 iPAQ pocket PCs in indoor office environment without receiver-side advertised window control. (b) Same configuration with receiver-side advertised window control.

¹In commodity 802.11b APs the maximum sojourn time in the AP FIFO buffer is in the 500 msec–1 sec range, a delay range that violates toll quality VoIP.

total throughput for TCP with receiver-side control is 5.192 Mbps whereas it is 5.189 Mbps without. A beneficial by-product of jitter control is that short-term unfairness stemming from AP buffer overflow—the non-persistent kind—is alleviated. We note that TCP-over-WLAN mitigates persistent unfairness but is still subject to the effects of transient unfairness. Figure 28 shows TCP throughput share across the 10 pocket PCs with and without receiver-side advertised window control. Transient unfairness resulting from buffer overflow, which can be significant for small time windows, is improved through jitter control. Whereas receiver advertised window control

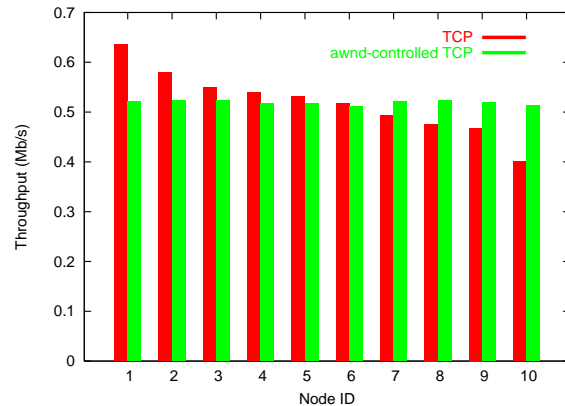


Fig. 28. TCP-over-WLAN transient unfairness with/without receiver-side advertised window control in indoor office environment.

directly limits the sender’s effective window size, virtual delay control aims to control a long-lived TCP flow’s sending rate by exploiting the property that steady-state TCP throughput is proportional to $1/\text{RTT}$ [31]. By delaying transmission of a TCP ACK packet for a suitable period from the time of arrival of a TCP data packet, the RTT experienced by the sender can be increased.

Figure 29(a) shows TCP-over-WLAN throughput and short-term fairness—captured as minimum over maximum throughput—when receiver-side delayed ACK control is activated. System throughput stays constant for virtual delay in the range 0–1000 msec, but starts to decline thereafter due to excessive throttling of sending rate. Short-term fairness, on the other hand, continues to improve with increased virtual delay, converging to a value near 1 at 600 msec. To achieve high throughput and good fairness—low jitter and good short-term fairness go hand-in-hand—virtual delay needs to be set between 600–1000 msec, a regime where AP buffer overflow and underflow (i.e., buffer becomes empty) are both prevented. Figure 29(b) shows a second by-

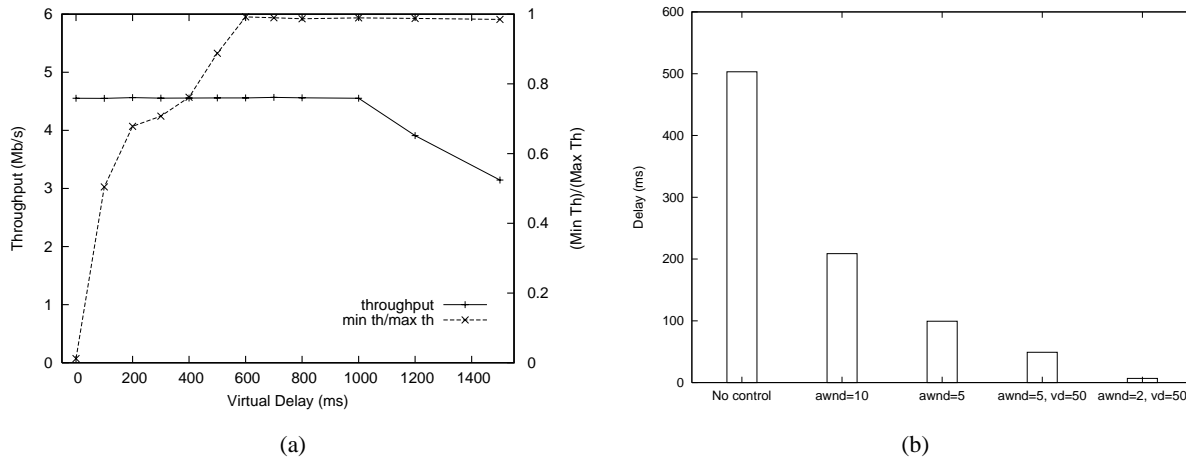


Fig. 29. (a) TCP-over-WLAN throughput and short-term fairness with receiver-side virtual delay control. (b) TCP-over-WLAN delay with receiver-side advertised window and virtual delay control.

product of jitter control: control of queuing delay at the AP buffer which can be up to 1 second in commodity 802.11b APs. In the Enterasys RoamAbout R2 AP, the maximum sojourn time with 1500 byte segment sizes is around 500 msec. With 10 pocket PCs running TCP, this limit is easily reached. For VoIP and other real-time applications, queuing delay must be held below a threshold value to meet the application's QoS requirements. Figure 29(b) shows that by setting the advertised window at the pocket PCs to 10 and 5, AP queuing delay can be decreased to 200 and 100 msec, respectively. Further reduction may be obtained by increasing virtual delay—at 50 msec virtual delay with advertised window size 5 a queuing delay of 50 msec can be attained—or decreasing the advertised window size. The experiments in Figure 29(b) only involve 10 pocket PCs. With more pocket PCs even an advertised window size of 1, by itself, is insufficient to keep queuing delay at bay, which necessitates joint advertised window and virtual delay control. The discussion on receiver-side traffic control focused on static control—the foundation for optimal dynamic control—without considering how to design feedback controls that achieve desired jitter, short-term fairness, and delay control. The latter is not a problem specific to WLANs—the same issues hold in low bandwidth wireline access links [35], [29]—and fall outside the scope of this paper.

V. CONCLUSION

In this paper we have studied WLAN and TCP-over-WLAN performance by incorporating the influence of physical layer channel diversity, inter-layer protocol dependencies, and issues surrounding their effective control. We have shown that DCF throughput degrades gracefully under increasing offered load and number of contending stations, but fairness and jitter undergo sharp transition at a critical offered load. We have shown how dynamic rate shifting can significantly degrade WLAN throughput under moderate multiple access contention, which may underlie part of the negative perception of 802.11 DCF throughput performance. We have shown that TCP-over-WLAN achieves scalable throughput which is facilitated by the self-regulating actions of DCF and TCP feedback control. As a consequence, we have shown that the TCP data/ack collision problem does not materialize. We have also shown that TCP-over-WLAN mitigates persistent unfairness stemming from physical layer channel diversity and neutralizes the detrimental effect of dynamic rate shifting on WLAN throughput. The remaining control dimension—jitter—may be effectively addressed in a legacy system compatible manner using receiver-side traffic control, providing a complementary deployment path to IEEE 802.11e for supporting VoIP and mixed applications. Several interesting challenges remain including study of multi-BSS WLANs incorporating inter-layer dependence—we suspect that the ad hoc wireless capacity results of Gupta and Kumar [16] and hybrid extensions [26], [27] are but a starting point—improvement of dynamic rate shifting algorithms that are less susceptible to collision-based frame errors (when TCP is running over WLAN this link layer problem is mitigated), and optimal receiver-side advertised window and virtual delay control to calibrate performance in wireless/wireline network environments.

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like to thank WildPackets for free use of their AiroPeek NX WLAN sniffing software.

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