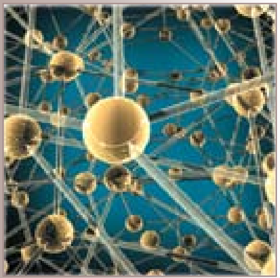

Load Balancing in IEEE 802.11 Networks

Because wireless stations independently select which access points (APs) to camp on, the total wireless station traffic on all available IEEE 802.11 network APs might be unevenly distributed. This load-balancing problem can lead to overloading and network congestion. This survey examines the problem, along with state-of-the-art network- and wireless-station-based solutions. It also presents experimental results using off-the-shelf IEEE 802.11 devices. As the results show, effectively balancing AP traffic loads can increase overall system throughputs.

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IEEE 802.11 wireless local area networks act as an infrastructure to provide wireless Internet access to homes, businesses, and public spaces. In Taipei, for example, the IEEE 802.11 networks deployed under the 2005 Mobile-City Project have made wireless broadband access service available across most of the city. First released in 1997, IEEE 802.11 technology has become widespread due to low deployment cost and high bandwidth. Other merits, such as ease of use and full interoperability with the predominant Ethernet, differentiate 802.11 from similar technologies such as 3G and IEEE 802.16.

To send and receive frames, a wireless station with an 802.11 interface uses an access point (AP) to a wired infrastructure. APs essentially bridge the wireless and wired worlds, serving as link-layer attachment points to the Internet. Because wireless stations independently select APs to camp on, traffic loads might be unevenly shared, leading to overloading and network congestion. The result is low data throughput for both the system and users. Traffic load problems are most likely to occur in public access areas such as stations, airports, and convention or exhibition sites. Researchers have developed several solutions to this problem, although existing designs continue to exhibit insufficiencies.

Load balancing approaches must address two primary issues:

- how to define and measure load-related metrics, and
- how to balance — or, at least dis-

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tribute — overall traffic load among all available APs.

Depending on which part of the network executes the load-distribution process, we categorize load-distribution schemes as wireless-station-based or network-based. Here, we discuss load metrics and various solutions to the problem, and compare system strengths and weaknesses based on results from our experiments with off-the-shelf 802.11 devices.

Overview: 802.11 Wireless Networks

Before a wireless station can receive an AP's frame-forwarding service, it must be associated with that AP. To discover available APs, wireless stations use either active or passive scans. In an *active scan*, the wireless station broadcasts a probe request frame specifying a particular service set identifier (SSID). If it matches an AP's SSID, the AP announces its presence by sending the wireless station a probe response. In a passive scan, the wireless station listens to beacon frames that the APs periodically broadcast. Then, based on the information grabbed from the probe response or beacon frames, the wireless station selects an AP to camp on. Almost all existing IEEE 802.11 adaptors favor the AP with the strongest received signal strength.

All associated wireless stations share an AP's bandwidth. The AP's throughput increases in proportion to the packet traffic load that its associated wireless stations add, provided that the overall traffic load doesn't exceed its capacity. When the AP's workload exceeds or approaches capacity, the throughput ceases to increase and results in overloading or congestion.

A simple way to increase overall system throughput is to deploy additional APs so that heavy traffic load can be distributed among them. Unfortunately, because each wireless station selects its AP independently, some APs might have many associations while others sit idle. This problem has motivated efforts to create load-balancing protocols for IEEE 802.11 networks. These protocols aim to make AP associations load-aware and thus help them avoid associations with congested APs. The ultimate goal is to increase overall system throughput.

Load-Aware AP Selection Metrics

Because having multiple traffic sources typically implies a high traffic load, a straightforward load metric is the number of wireless stations associated with an AP.[1] However, IEEE 802.11 doesn't include wireless station count as an information element in probe response or beacon frames. Some vendors and researchers have proposed that these frames include this information. Their efforts contributed to IEEE 802.11e, which includes current wireless station population and AP traffic elements in the QoS Basic Service Set (QBSS) load element. However, this element isn't always present in beacon or probe response frames, which somewhat impedes the schemes' widespread applicability. (The information element is present if both management information base [MIB] attributes for APs, `dot11QosOptionImplemented` and `dot11QBSSLoadImplemented`, are set to true.)

Load-Balancing Metrics

Network-side managers can also request every AP's wireless station count to achieve network-wide load balancing. Unfortunately, the managers can't access this information using the Simple Network Management Protocol (SNMP) because wireless station count hasn't been defined in MIB-II, IEEE802dot11-MIB, or any other standardized management information base.[2] Although some vendors have extended IEEE802dot11-MIB to include such information, the extensions are applicable only to their own products. An alternative is to extend a standardized protocol such as Inter Access-Point Protocol (IAPP) to include relevant information elements.

The wireless station count alone can only roughly estimate an AP's workload because traffic conditions vary significantly among wireless stations and can change over time. Vendors use other metrics for pragmatic reasons. For example, IEEE 802.11e and US patent 2004/0039817[3] propose channel utilization — that is, the percentage of time an AP is busy transmitting or receiving data during some interval — as a channel loading gauge. Channel utilization isn't an appropriate AP selection metric, however, because it doesn't capture the transmission capabilities of respective APs. For example, an IEEE 802.11g AP at 80 percent capacity can offer more bandwidth than an IEEE 802.11b AP at 40 percent capacity.

Because overloading often entails a jammed sending queue, an AP transmission queue's frame drop rate during real-time sessions is

Proposal	Needs a server?	Load-distribution control	Changes required at access point (AP)?	Changes required at wireless station (WS)?
Dynamic load balance	No	WS	Yes	Yes
Maximizing local throughput	No	WS	Yes	Yes
Vasudevan and colleagues' scheme	No	WS	No	Yes
Application-Layer Load Distribution Protocol	Yes	WS	No	Yes
Virgil	Yes	WS	No	Yes
US patent 2004/0039817	No	WS	Yes	Yes
Load balancing agent	No	AP	Yes	No
Cell breathing	No	AP	Yes	No
Admission control server	Yes	Server	Yes	Yes
Bejerano and colleagues' scheme	Yes	Server	No	Yes
US patent 2005/0213579	No	Switch	Yes	No

Table 1. Summary of load-balancing methods in IEEE 802.11 networks.

another load metric.[4] Researchers have also observed that we can estimate queuing and channel-contention delay, which reflect an AP's load level based on the delay between the periodic beacon frames' scheduled and actual transmission time.[5] However, these low-level estimations assume certain implementation conventions and might not apply to all products.

Throughput: Measuring Effectiveness

Throughput is a common metric for quantifying a load-balancing scheme's effectiveness. Given this, Hector Velayos and his colleagues take link-layer throughput as a direct measure of load.[6] Some AP selection heuristics favor APs that maximize expected throughput[1] or potential bandwidth.[5] However, throughput or bandwidth usage is affected by time-varying channel conditions — which are intrinsic to IEEE 802.11 networks — as well as by bursty traffic patterns. Given this, we can typically take only a long-term average (on a scale of seconds or tens of seconds[7,8]) as an estimate.

Yigal Bejerano and his colleagues[7] asserted that the load induced by a wireless station w on its associated AP a is the time that a takes to provide w one unit of traffic. Accordingly, the load that w imposes on a is inversely proportional to the effective bit rate that w experiences. This definition aims to predict an AP's load using effective bit-rate information. However, the predicted load coincides with observed workload only if w consumes all the bandwidth allocated to it — that is, if w has an infinite backlog of packets to send and receive.

For wireless stations with bounded or dynamic bandwidth demands, we argue that an AP's load is better expressed in terms of effective or observed throughput. Given a load metric, we can gather a baseline for under-loaded AP operations and, when the load reaches some predefined threshold, we can assume overloading or congestion.[4] This is an absolute definition of overloading. The definition of overloading can also be relative. That is, an AP is overloaded if its load level exceeds the current average by a certain amount.[6] Researchers have introduced a balance index to characterize the degree of load balance among servers.[9] For n APs numbered 1 to n that serve the same set of wireless stations, let L_i denote the amount of aggregated load imposed on AP i. The balance index β is defined as[6,10,11]

$$\beta = \frac{(\sum L_i)^2}{n \times \sum L_i^2}. \tag{1}$$

The value of β becomes 1 when all APs share an equal load, and it approaches $1/n$ in case of extreme imbalance. If L_i in Equation 1 denotes the bandwidth share received by wireless station i for n contending wireless stations (numbered from 1 to n), then the value of β essentially quantifies the fairness of bandwidth share among wireless stations.[1]

All existing load-balancing protocols distribute traffic load by managing associations between APs and wireless stations. As Table 1 shows, we can classify such protocols according to the part of the network that manages them: the wireless stations or the network.

Wireless-Station-Based Load Distribution

In this approach, wireless stations select an AP that maximizes their potential benefits (such as potential bandwidth,[5] for example). APs act passively throughout this selection process. Many wireless-station-based approaches are not designed to achieve system-wide load balance — the stations simply select APs according to their own interests. However, seeking an AP that provides the maximal available bandwidth implicitly implements least-load-first AP selection, a widely used load-balancing heuristic.

Estimating Load Conditions

Wireless stations can acquire AP load conditions in several ways. They can, for example, measure channel utilization or the delay between the scheduled and actual beacon-frame transmission times.[5] Such approaches require no assistance from any network-side entity. Alternatively, an AP can broadcast its current wireless station population or traffic level in a probe response or beacon frame — preferably with a QBSS load element if the AP supports IEEE 802.11e. Examples of this type include maximizing local throughput[1] and the dynamic load-balance approach.[12]

System administrators can also deploy a dedicated server to assist in load measurements. In the Application-Layer Load Distribution Protocol, a wireless station first associates with an AP, then accesses its load metric (throughputs) from a stand-alone server.[8] The server uses SNMP to maintain load states for all APs residing in its administrative domain by periodically polling the APs' throughput-related MIB objects. After estimating its own bandwidth consumption, the wireless station then decides whether it should conduct a handoff to distribute the load.

In the Virgil project,[13] a wireless station briefly connects to each available AP for a performance test. For each AP, the wireless station generates test traffic to a predeployed Internet server. The wireless station then selects the AP that provides the highest performance service for a long stay, based on expected bandwidth and round-trip time.

Association Management

Wireless stations can manage their AP associations statically or dynamically. In static cases, a wireless station performs AP selection prior to associating with the target AP and doesn't reassociate to other APs as long as the association holds. Static AP selection's drawback is that it can't adapt to network changes. In contrast, with dynamic AP selection, a wireless station can reassociate with another AP even if the current association still holds. This approach is better suited to highly dynamic networking environments. However, it can also lead to unstable associations — or ping-pong effects — when associations repeatedly change from one AP to another.

Ping-pong effects can occur when wireless stations simultaneously switch APs without coordination. If, for example, we suddenly power up an AP near a congested AP, all its associated wireless stations might detect the new AP's presence and decide to switch to it almost simultaneously. Consequently, the new AP will immediately become overloaded due to bursty migrations; when all wireless stations decide to switch back, the scenario repeats.

To avoid ping-pong effects, developers should either use static AP selection or find a way to distribute reassociations over time. In one project, for example, a wireless station periodically searches for the best AP with the least load.[8] When it finds the best AP, rather than immediately switching to it, it generates a random value d. The wireless station can switch to the best AP only after it identifies it as the best for d successive times. Such a back-off scheme suppresses association migration bursts.

Benefits and Drawbacks

Letting wireless stations select APs lets developers use off-the-shelf APs with little to no modification.[5,8] However, when wireless stations select APs based on their own interests, a network-wide load balance seldom results. As an alternative, system administrators can choose to distribute load through a network-side entity.

Network-Based Load Distribution

In a network-based approach, a network-side entity (such as an AP, a switch, or a dedicated server) controls the AP's load distribution.

Wireless stations behave passively in modifying their associations with APs.

Basic Techniques

APs can control their own load level using three basic techniques: coverage adjustment, admission control, and association management.

In coverage adjustment, crowded APs reduce their beacon signal's transmission power so that new wireless stations are less likely to discover them.[11] APs also collaborate in adjusting their radio coverage patterns to ensure that lightly loaded APs cover more area and that coverage holes are eliminated.[14,4] Developers have applied this technique, referred to as *cell breathing*, to cellular telephony systems.

In admission control, an overloaded AP simply rejects new association requests. Non-overloaded APs grant association requests on the basis of their own workload status — that is, they accept requests if the predicted load level after the association doesn't exceed some threshold. An example here is the load balancing agent approach.[6]

In association management, a crowded AP can send an unsolicited disassociation frame to selected, associated wireless stations (possibly using a status code indicating that the AP can't handle all currently associated stations). The hope is that the targeted wireless stations would reassociate with other lightly loaded APs. Theoretically, the best disassociation candidate is one that would then reassociate in a way that balances the load among related APs. However, it's impractical to seek such an optimal solution in a fast-changing networking environment, as the optimum holds only for the current state. For a heuristic that finds good candidates, the AP might need to know the neighboring APs' load levels and the AP set that's accessible to each associated wireless station. Also, the ping-pong effect might occur here if we let disassociated wireless stations be disassociated again in the future.

Estimating Global Load Distribution

For a global view of load distribution, APs could exchange load status information via a wired backbone. To achieve this, we could reuse existing protocols, such as IAPP, with some slight modifications. APs that identified themselves as overloaded could then use the approaches we just discussed to relieve their loads.[6,14] Alternatively, they could use a dedicated wired-infrastructure server to collect load-related information. An example here is the admission control server approach.[10] In this case, the server would learn of the traffic load distribution and then recommend or instruct designated wireless stations to change their AP associations. It could do this by communicating with the peers running at the wireless stations. The ability to estimate each wireless station's consumed (or potentially demanded) bandwidth could further facilitate association handoff decisions. This is because the information makes it easy to

- determine the set of eligible APs that fulfills the implicit bandwidth demand of a particular wireless station and
- predict load shift between APs for each feasible handoff and thereby determine the best handoff target.

Load estimation is complicated by the current common practice of supporting multiple transmission rates (IEEE 802.11a, for example, supports eight transmission rates, ranging from 6 to 54 Mbits per second). The actual transmission rate between an AP and an associated wireless station depends on the underlying time-varying channel conditions. To make things worse, the throughput of wireless stations with high transmission rates can actually suffer when low-rate wireless stations are present.[15] This makes handoff decisions difficult in that the load shift due to association migrations is hard to predict.

Switch-Based Approach

It's also possible to use switches to manage AP associations. One such solution uses a centralized mechanism wherein a switch connecting a set of APs provides load-balancing functionality within a wireless LAN.[16] In this approach, the APs interact with the switch to make decisions on certain operations related to accepting new stations. Given this, the switch and APs must share some (proprietary) protocol; interoperability with different vendors' APs might be challenging.

Experimental Results

We conducted experiments to measure and compare network performance with and without load-distribution schemes. In the experiments, we placed two identical IEEE 802.11a APs (Cisco

AIR-SP1220A) in close range with a partition between them. These APs, operating on channels 56 and 64, respectively, were connected through a 100-Mbps switch to a PC running Linux kernel 2.4.20. We isolated the Ethernet connecting all these devices from other LANs to minimize the potential influence from background traffic. For our wireless stations, we used a set of notebook PCs equipped with an IEEE 802.11 a/b/g Personal Computer Memory Card International Association interface (D-Link DWL-AG660); each ran Linux kernel 2.4.33 with a MadWiFi 0.9.2 driver (http://madwifi.org). Figure 1 shows the experimental setup; Table 2 shows the reported signal strengths.

To measure throughput and packet-loss rate, we used Iperf (http://dast.nlanr.net/Projects/Iperf/). An Iperf client ran at each wireless station and generated fixed-size User Datagram Protocol (UDP) segments at a constant rate to an Iperf server (the PC) on the Ethernet. (Although Internet traffic is generally composed of TCP traffic, we didn't consider it because protocol characteristics — such as slow start and congestion avoidance — might influence our results' validity. By eliminating TCP involvement, our statistics fully represent link-level behavior to the greatest possible extent.) We set the UDP buffer size to a default value (64 Kbytes). Source data rates were all identical and varied from 4 to 24 Mbps. Finally, each test traffic lasted one minute, and we gathered all statistical results at the Iperf server.

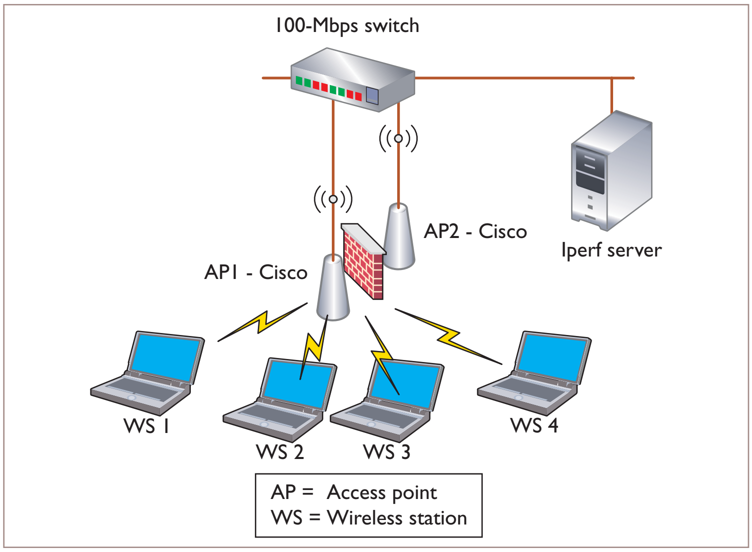

Figure 1. Experimental setup. Wireless stations 1, 2, and 4 (WS1-WSs) were Pentium M740s (1.73 GHz) with 1 Gbyte of RAM; WS3 was a Pentium IV (1.7 GHz) with 256 Mbytes of RAM.

Table 2. Mean signal level (in decibels above or below one milliwatt) for the experiment's four wireless stations.

	WS1	WS2	WS3	WS4
AP1	–52.9	–46.6	–50.9	–48.5
AP2	–63.2	–60.3	–66.1	–60.5

Testing without Load Balance

In the first setup, we didn't use any load-distribution protocol. We sequentially added four wireless stations to the network; each was within a meter of an AP (AP1) and was placed directly in front of it. These wireless stations remained stationary during the test. Consequently, all wireless stations were associated with AP1 for its stronger signal strength.

We used the Iperf server's aggregate throughput as network throughput; in this case, it was generated only by AP1's four stations. Figure 2a shows the network throughput's relationship to the number of associated wireless stations. The maximum throughput (31.7 Mbps) was upper bounded by one AP's real capacity, which was slightly higher than half of its nominal capacity (54 Mbps). This is consistent with the finding of previous independent studies. When we associated only one wireless station with the AP, the network throughput completely reflected the given load. When two or more wireless stations were associated, the throughput no longer increased linearly with the given load, even if the aggregate load didn't exceed one AP's real capacity. As we see it, this occurred because, as more wireless stations contended for the channel, it reduced the effective bandwidth that each wireless station received. When the effective bandwidth was inadequate to bear a wireless station's traffic, many outgoing packets were dropped as the sending buffer was mostly full. Our view is supported by measured average packet-loss rates, which increased monotonically with the number of contending wireless stations (see Figure 2b).

Testing with a Load-Distribution Protocol

Our second setup was identical to the first one, except that we applied a wireless-station-based load-distribution protocol.[8] We ran an "information collector" software module on the PC, which also ran the Iperf server. The information collector maintained wireless station count for each AP and routinely used SNMP to collect

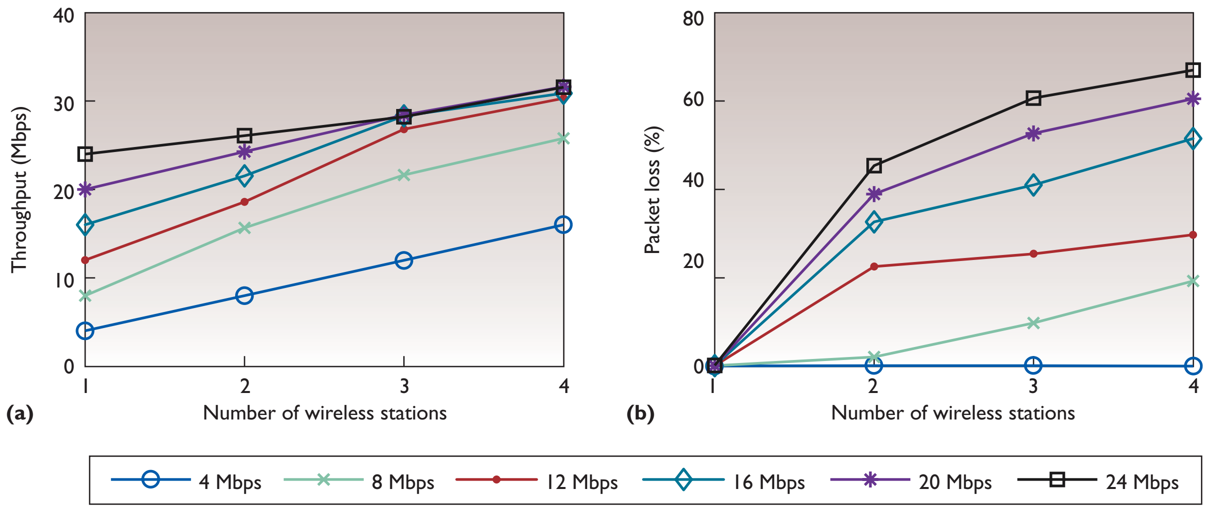

Figure 2. Experimental results without load balance. (a) Throughput results are consistent with other studies: maximum throughput is upper bounded by one AP's real capacity. (b) Packet-loss rate increases with the number of wireless stations contending for the channel.

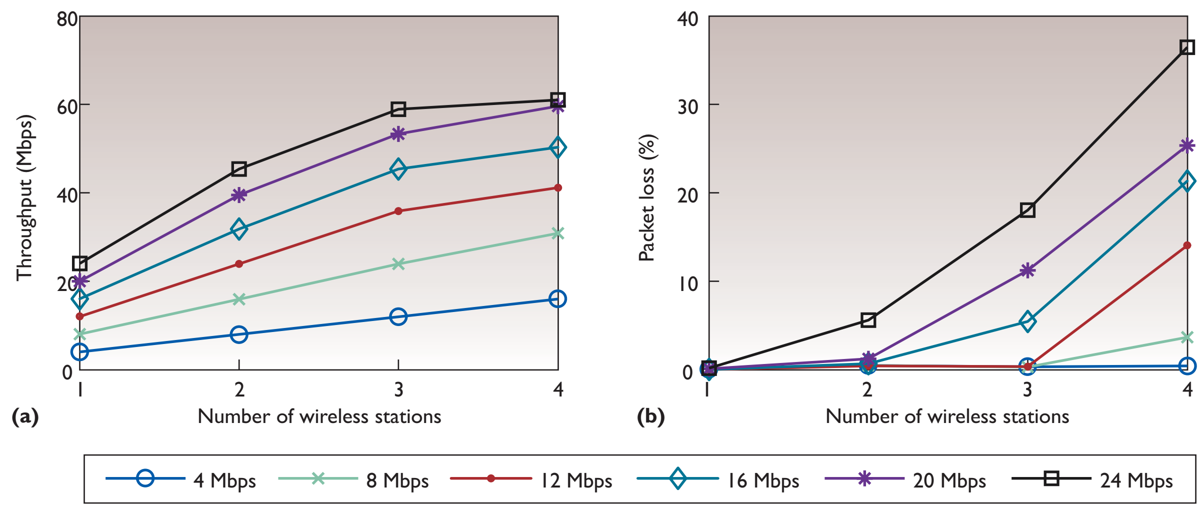

Figure 3. Experimental results with load balance. (a) Throughput with load balance. (b) Packet-loss rate with load balance.

throughput-related MIB objects from the APs. To manage associations, we ran a load control entity (LCE) application at each wireless station. Once a wireless station associates with an AP (the one with the strongest received signal strength), the LCE requests the number of currently associated wireless stations and each available AP's interface speed from the information collector. Based on this information, the LCE computes the AP's normalized residual bandwidth (NRB) after admitting the wireless station's possible immigration. The LCE then selects the AP with the highest possible NRB to camp on, which sometimes causes reassociations. Consequently, not all wireless stations in this setup were always associated with AP1, so overall network throughput was contributed by both APs.

As Figure 3a shows, compared with our first setup's results, this load-distribution scheme significantly improved network throughputs. In particular, it doubled maximum throughput. The observed improvements were due to effective load distributions among available APs, which the corresponding results of average packet-loss rate confirms (see Figure 3b).

Generally speaking, the throughput-improvement ratios — that is, the ratio of increased throughput to the original — were closely related to the amount of traffic load the wireless stations imposed on APs. When the aggregate traffic load was less than 32 Mbps, the improvement ratios ranged from –10.0 percent to 28.5 percent, with an average value of 2.5 percent. In contrast, for traffic loads greater than 32 Mbps, the ratios ranged from 19.5 percent to 108.6 percent, with an average value of 64.6 percent. For each specific workload, the improvement ratio was higher, with fewer contending wireless stations. For example, consider three cases:

- two wireless stations that each generated 24 Mbps traffic,
- three wireless stations that each generated 16 Mbps traffic, and
- four wireless stations that each generated 12 Mbps traffic.

Although each case imposed the same traffic load on APs (48 Mbps in total), their throughput-improvement ratios were 74.0 percent, 60.3 percent, and 35.7 percent, respectively.

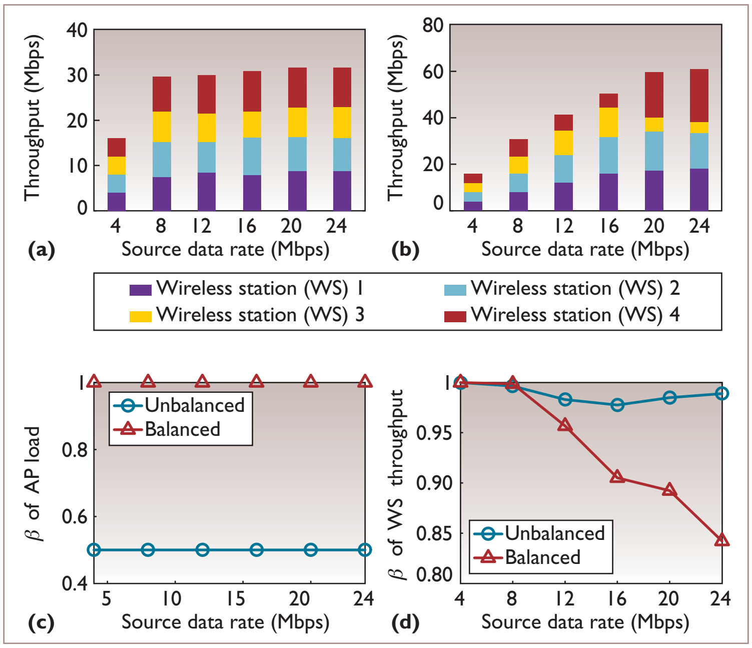

Figure 4. Comparing the experimental setups. We first compared the throughputs of four contending wireless stations (a) without the load-balancing protocol and (b) with the load balancing protocol. We then recorded balance indices for (c) access-point loads and (d) wireless station throughputs. "Unbalanced" and "balanced" correspond to the results without and with the load balancing protocol, respectively.

Comparing the Two Schemes

Figures 4a and 4b compare throughputs for four wireless stations with and without the load-balancing scheme. As Figure 4c shows, the load-balancing protocol successfully increased the balance index of the AP load from 0.5 to 1, which implies that the AP load was perfectly balanced (each AP served two wireless stations and each wireless station generated identical traffic load). However, the protocol didn't equalize each wireless station's received bandwidth (see Figure 4b). With a 24-Mbps traffic load, for example, measured throughputs for wireless stations 1 through 4 were 18.3, 15.1, 4.84, and 22.8 Mbps, respectively. We believe that wireless station 3's poor throughput performance was due to its inferior computing/storage capability. Although this slight variation had an insignificant impact when all wireless stations were contending for a single AP (Figure 4a), it made a difference when only two wireless stations were in contention for a single AP. The effect was particularly significant when all wireless stations used high data transmission rates (see Figure 4d).

Such a performance difference wouldn't appear in a software-based simulation environment, in which every wireless station acts homogeneously. In practice, a wireless station might still experience low packet-loss rates (or, equivalently, high throughput) even when the serving AP was congested. Similarly, a load-balanced state that greatly increased system throughput didn't necessarily produce uniformly low packet-loss rates. The lesson we learned here is that fairness is an independent issue, and load balancing won't necessarily resolve it. This view is supported by the original IEEE 802.11, which doesn't guarantee an equal share of available bandwidth among contending wireless stations.

Network load sharing warrants further investigation, not least because IEEE 802.11 technology has been evolving into other forms, such as mesh (IEEE 802.11s) and AP-independent direct link setup (IEEE 802.11z). Various uses for it have also emerged, such as in vehicular communication (IEEE 802.11p) and in accommodating robust audio-video transport streams (IEEE 802.11aa). These ongoing developments give rise to new factors that might motivate or even revolutionize load-sharing methodology.

Apart from technological progress itself, an important outstanding task is to devise effective means to share traffic load among APs of different generations with distinct capabilities. A common scenario is a network of IEEE 802.11b, 802.11g, and emerging 802.11n APs that are phased in over time. In addition, load balancing also gives rise to subtle conflicts of interest for system operators and users; in our view, a better-balanced system favors network operators but might be not advantageous to users. Clearly, much effort remains in this area; our intent with this article was to offer a sufficient, informative background for future studies in the research community.

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