ACORN: An Auto-configuration Framework for 802.11n WLANs

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***Abstract*—The wide channels feature combines two adjacent channels to form a new, wider channel to facilitate high data rate transmissions in MIMO-based 802.11n networks. Using a wider channel can exacerbate interference effects. Furthermore, contrary to what has been reported by prior studies, we find that wide channels do not always provide benefits in isolation (i.e., one link without interference) and can even degrade performance. We conduct an in-depth, experimental study to understand the implications of wide channels on throughput performance. Based on our measurements, we design an auto-configuration framework called ACORN for enterprise 802.11n WLANs. ACORN integrates the functions of user association and channel allocation, since our study reveals that they are tightly coupled when wide channels are used. We show that the channel allocation problem with the constraints of wide channels is NP-complete. Thus, ACORN uses an algorithm that provides a worst case approximation ratio of $O(\frac{1}{\Delta+1})$, with Δ being the maximum node degree in the network. We implement ACORN on our 802.11n testbed. Our evaluations show that ACORN (i) outperforms previous approaches that are agnostic to wide channels constraints; it provides per-AP throughput gains ranging from *1.5x* to *6x* and (ii) in practice, its channel allocation module achieves an approximation ratio much better than the theoretically predicted $O(\frac{1}{\Delta+1})$.**

I. Introduction

The IEEE 802.11n [1] is based on the use of MIMO technology and promises drastically improved throughputs as compared to legacy 802.11 systems (a / b / g). In order to achieve high data rates (> 100 Mbps), 802.11n supports a feature called wide channels. With wide channels, two adjacent channels can be combined to form a new, wider frequency band; this is expected to support transmissions at higher bit rates (i.e., bandwidth). The default channel width is 20 MHz and it is increased to 40 MHz when wide channels are activated. To realize increased data rates, 802.11n uses 114 subcarriers with 40 MHz channels (as compared to 56 subcarriers with 20 MHz channels) in a given OFDM symbol.

The use of wide channels however, has associated caveats. The links using 40 MHz channels project increased interference on other links and can negatively impact the total network throughput [2]. On the other hand, prior studies have only reported results suggesting that wide channels would yield significantly higher throughput in settings *without* interference [2], [3]. Surprisingly, our experiments suggest the contrary in quite a few cases; the throughput with wide channels (for a single link in isolation) can be even worse than that with a single 20 MHz channel. We carefully examine the reasons behind this observation by conducting both physical layer (PHY) as well as higher layer experiments. Our key findings from the experiments are summarized as follows.

Wide channels without interference: First, with a fixed transmission power (T_x), there is about a 3dB decrease in the signal strength per subcarrier when wide channels are employed. Thus for a fixed T_x, the Bit Error Rate (BER) and the Packet Error Rate (PER) with wide channels is always greater than or equal to that without wide channels. Therefore, the throughput observed with wide channels is almost always "less than double" of that without them [1]. Second, using a higher number of subcarriers with wide channels increases the likelihood of experiencing errors. We find that links of poor quality (i.e., low SINR) are the ones that are most affected by these factors; the throughput on such links with wide channels is worse than without them. More importantly, as discussed later, the existence of a single low-SINR client in a cell (that uses wide channels) can degrade the long-term throughput of the entire cell due to the 802.11 performance anomaly [4]. One might argue that these adverse affects of wide channels can be alleviated by using a higher T_x at the APs. However, note that T_x cannot be increased beyond a specified maximum value; this value is the same for both 20 and 40 MHz channels as mandated by the 802.11n standard [1]. In addition, increasing T_x may project additional interference on other links.

Wide channels and interference: The use of wide channels projects interference over a larger spectral width (40 MHz as opposed to 20 MHz). Thus, the wider channels need to be carefully assigned to cells in a dense enterprise WLAN setting. Moreover, note that due to the 3 dB reduction in the per-carrier signal strength, transmissions with the wider bands are more susceptible to interference.

The above observations suggest that WLANs should employ wide channels with care. In this paper, we design ACORN, an <u>A</u>uto-<u>CO</u>nfigu<u>R</u>ation framework for enterprise 802.11<u>N</u> WLANs. ACORN jointly performs the functions of channel allocation and user association. As discussed above, the existence of poor quality clients impacts the cell-wide

[1] In an ideal setting, one would expect that doubling the channel width would yield twice the throughput.

performance; therefore, intelligent user association is critical in facilitating the throughput gains from wide channels. In brief with ACORN, clients make association decisions not in a selfish / greedy manner, but by considering their impact on cell throughput. APs decide whether or not to use wide channels by considering factors such as interference, towards achieving network-wide performance gains. To our best knowledge, ACORN is not only the first system to address the application of wide channels in enterprise WLANs but also the first system to consider the use of two distinct channel widths while performing joint channel allocation and user association.

The main contributions of our work are the following:

- We conduct extensive PHY layer experiments using WARP [5] and higher layer experiments on our 802.11n testbed, to validate that the performance can indeed degrade in settings without interference if wide channels are used.
- Leveraging the insights from our experiments, we design ACORN - an auto-configuration system for 802.11n WLANs. ACORN jointly executes user association and channel allocation with wide channels.
- We show that the channel allocation module of ACORN achieves a theoretical worst case approximation ratio of $O(\frac{1}{\Delta+1})$ as compared to an optimal algorithm, where Δ is the maximum node degree in the network (the problem is shown to be NP-complete).
- We implement ACORN on our 802.11n testbed and show that (i) it provides significant performance benefits (ranging from *1.5x* up to *6x*) over the state-of-the-art schemes designed for legacy 802.11 (which typically employ bands of a single width) [2] and (ii) in practice, ACORN's channel allocation performs better than the theoretical worst case approximation.
- We evaluate ACORN with both synthetic UDP / TCP traffic as well as realistic HTTP workloads. We show that ACORN improves performance for all the considered traffic types.

The rest of the paper is organized as follows. In Section II we provide brief background on the 802.11n PHY and discuss related work. Section III describes our PHY and higher layer measurements that provide an understanding of the behavior with wide channels. We present the design of, and analyze the algorithms included in ACORN in Section IV. Section V describes the system implementation and our experimental evaluation. We discuss ACORN's applicability to other deployments in Section VI. Our conclusions form Section VII.

II. Background and Related Studies

In this section, we first provide brief background on 802.11n. We then describe related previous work.

A. 802.11n Background

802.11n technology offers significant improvements over the legacy 802.11a / b / g protocol family. At the PHY layer, 802.11n utilizes MIMO communication with OFDM. Two modes of MIMO operation are feasible with 802.11n: **(i)** *Spatial Division Multiplexing (SDM)*, which transmits multiple independent data streams and thus achieves higher data rates and **(ii)** *Space Time Block Coding (STBC)*, which targets higher reliability and range by transmitting a redundant copy of the signal. Typically, vendors implement rate adaptation algorithms with 802.11n, which choose the mode of MIMO operation based on the link quality and other parameters. The MIMO operation together with the wide channels feature contributes to the throughput benefits offered by 802.11n.

B. Related Work

802.11n Experimental Studies: In [2], Shrivastava *et al.* identify that 802.11n throughput performance is limited by the CSMA / CA access policy inherited from the 802.11 legacy protocol family. In addition, they provide insights on increased interference due to wide channels, using a previously proposed model [6]. They recommend using wide channels on the 5 GHz band (in contrast to 2.4 GHz) since it offers more orthogonal channels and hence less potential interference. However, their conclusions cannot explain why an isolated link does not always enjoy a higher throughput with wide channels, as compared to the case without them, which we show to be the case in practice. Visoottiviseth *et al.* [3] compare the performance between commodity 802.11g and 802.11n devices. However, this work does not examine wide channels in depth.

The above studies have either reported that wide channels decreased the throughput due to increased levels of interference [2] or that wide channels increased the throughput when used for a single link in isolation [2], [3]. On the contrary, we experimentally show that wide channels may degrade the performance even for a single link, in addition to the degradation for multiple interfering links.

Orthogonal Frequency Division Multiplexing (OFDM): OFDM divides the allocated spectrum into smaller tones (subcarriers) that are orthogonal to each other. Each subcarrier carries data at lower rates; however together they maintain the total data rate. OFDM systems have the advantage of better coping with narrowband interference and fading [7]. There are many studies that try to improve OFDM performance. For example, Rahul *et al.* [8] implement a downlink OFDM PHY for WLANs that performs rate adaptation per subcarrier. Subcarrier power allocation is examined in [9]. In this work, we are not interested in changing the PHY layer functions of 802.11n OFDM; we examine the effects of the PHY layer (with wide channels) on the higher layers and propose a solution towards improving performance without requiring significant changes at the core PHY / MAC functionality.

Channel Width Adaptation: Commodity 802.11 hardware vendors have also implemented a function that uses channels of varying width. These systems can flexibly use 5, 10, 20 and 40 MHz bandwidth [10], [11]. In [12], the authors propose a channel width adaptation algorithm that can dynamically choose a bandwidth to satisfy an optimization criterion. Although the authors discuss the potential usage of

[2]While these results are specific to the capabilities of our hardware, we discuss the applicability of ACORN with other hardware in Section IV.

their algorithm in a WLAN context, the algorithm is designed assuming two communicating nodes and its applicability in enterprise WLANs is not studied. [13] proposes a spectrum allocation solution that leverages the flexible channel widths, by considering the load in each AP. It only addresses the assignment of different channels with a given client population (i.e., user association is not studied). In contrast, we show that user association and channel allocation (using wide channels in our case) is tightly coupled. We examine the impact of different channel widths on 802.11n enterprise WLAN performance by jointly considering user association and channel allocation.

Resource Allocation: Resource allocation in WLANs usually refers to power / rate control and channel selection. User association is very tightly related with these functions; therefore, in many cases they are studied together.

Static channel allocation is shown to have associated fairness issues and thus, Mishra *et al.* [14] propose a dynamic algorithm based on frequency hopping. In [15], the same authors formulate the channel assignment problem as a graph coloring problem and solve it. Kumar *et al.* [16] formulate a utility optimization problem that accounts for user association. All of the above efforts however, study the problems of channel selection or user association independently. In [17] and [18] the problem of jointly performing frequency selection and user association is studied. Mishra *et al.* [17] provide a centralized approach, while Kauffman *et al.* [18] provide a distributed solution based on the Gibbs sampler. In [19], the authors study the interaction between channel allocation, power control and user association.

All of the above (independent or joint) network optimization solutions are designed for legacy 802.11 systems that use single channel widths. The complexities associated with wide channels render the above solutions inapplicable to 802.11n. To the best of our knowledge, we are the first to study the joint problem of channel selection and user association in 802.11n WLANs, considering two distinct channel widths.

III. Wide Channels are not the Panacea

In this section, we first analyze the behavior of wide channels at the PHY layer. Later, we examine the impact of these PHY observations on the higher layers.

A. Wide channels micro-effects

802.11n leverages the OFDM-based PHY to implement the wide channels feature. OFDM is inherited from legacy 802.11 systems. 802.11a / g modulate 52 subcarriers in an OFDM symbol of 4μsec duration. The OFDM subcarriers together form a 20 MHz channel (or band). Four subcarriers are for pilot tones; thus, 48 subcarriers effectively carry data in an OFDM symbol. With 802.11n, the number of modulated subcarriers is increased to 56; 52 subcarriers carry data and four are for pilot tones. This results in a maximum nominal bit rate of 65 Mbps for a single data stream [3]. Wide channels utilize two adjacent channels simultaneously and employ 114 sub-carriers (108 data and 6 pilot) over a total of 40 MHz bandwidth. As one might expect, the nominal bit rates with 40 MHz are slightly higher than double of their 20 MHz counterparts for the same modulation. However, there is an important factor that can negatively impact the achievable throughput in a 40 MHz channel; the SNR experienced is lower with wide channels than when a 20 MHz band is used. To understand why this is the case, let us first look at the impact of increasing the number of subcarriers on (a) the thermal noise and (b) the energy per subcarrier.

[3] This assumes a 800$n$sec guard interval (GI). The option for a shorter GI (400$n$sec) is also available in 802.11n; this reduces the symbol duration to 3.6μsec and further increases the data rate. For more details see [1] and [7].

Impact of wide channels on thermal noise: The total thermal noise in a 40 MHz channel is higher than that in a 20 MHz channel. The Wi-Fi noise floor, N, can be calculated as follows [20]:

$$N(in\ dBm) = -174 + 10 \cdot log(B) \quad (1)$$

where B is the bandwidth of the channel in Hz. It is easy to see that the noise in a 40 MHz channel is about 3 dBm ($10log2$) higher as compared to a 20 MHz channel. If one assumes that the noise is uniformly distributed across the subcarriers, the *noise per subcarrier* can be expected to remain almost the same for both the 20 MHz and 40 MHz channels.

Impact of wide channels on subcarrier energy: The 802.11n standard [1] mandates the use of the same maximum transmit power with and without wide channels. In an OFDM system, the transmit energy is uniformly distributed across the subcarriers. Since wide channels use 114 subcarriers and the total transmit power remains the same, the energy per subcarrier is theoretically reduced to 49% of that of 20 MHz bands (approximately halved). Expressed in dB, this translates to about a 3 dB reduction in the energy per sub-carrier. This in turn, can have a negative impact on the performance. In practice, device manufacturers typically reduce the per-subcarrier power by 3 dB since the power amplifiers do not have the resolution required to apply the exact theoretical value. This is considered sufficiently accurate since a 1% error is not significant.

Considering the two factors together, we postulate that:

- For the same transmission power (T_x), the SNR of a signal is reduced by 3dB with wide channels. A reduction similar to this postulated value, is seen in the energy per subcarrier in our experiments (discussed below); the noise per subcarrier remains almost the same as predicted theoretically. Thus, **the SNR per subcarrier is halved**; combined with the increased probability of error due to the larger number of subcarriers (each subcarrier experiences a different fade), a BER increase is expected.
- In order to achieve the same SNR on a link, with both 20 and 40 MHz channels, one needs to increase the transmission power in the latter case. However, this might not be possible given power budget constraints; in addition, 802.11n dictates the use of the same maximum power with and without wide channels.
- One might expect these factors to primarily affect poor quality links since they are the ones that are most susceptible to the lowered SNR due to wide channels.

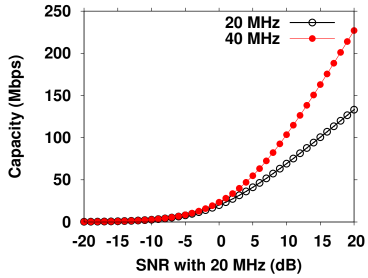


Fig. 1. Theoretical capacity calculated by Shannon's theorem. For low-SINR values, capacity of wide channels is similar to that of a 20 MHz channel.

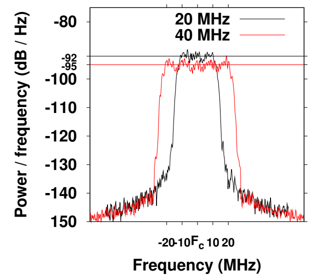


Fig. 2. PSD estimate with different channel widths. Wide channels result in a 3 dB reduction on the signal strength per sub-carrier.

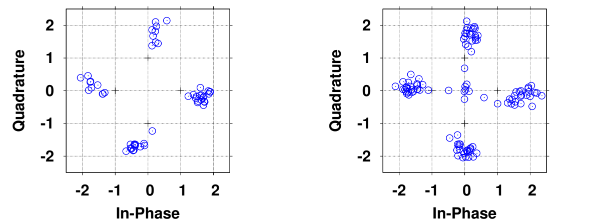


Fig. 3. Received constellations with different numbers of subcarriers. Although one can transmit more bits in a symbol with wide channels, the reception is more likely to be distorted (on the right) as compared to the case without wide channels (left).

With additive white Gaussian noise (AWGN), one can deduce the above observations from Shannon's theorem on wireless channels [20]. The capacity C of an AWGN channel (in bits per second) with bandwidth B (in Hz) is given by:

$$C = B \cdot log_2(1 + SNR) \qquad (2)$$

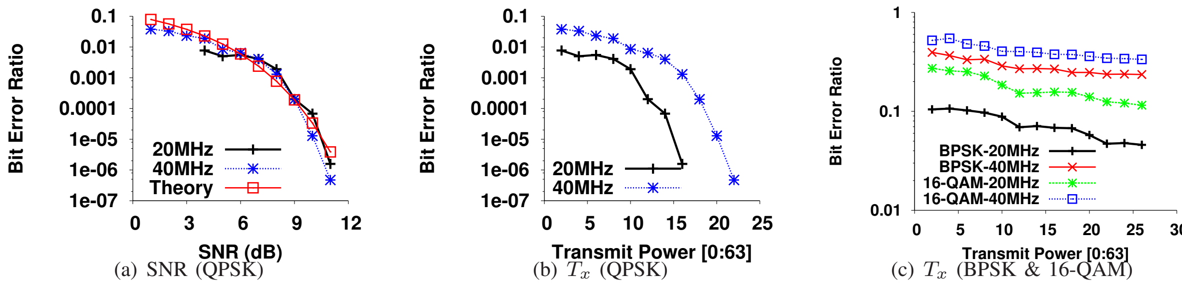
Here, the SNR is unitless (not in dB) and represents the ratio of the signal energy to the noise. One can convert this ratio to decibels by using the equation $dB = 10 * log_{10}(ratio)$. From this equation, one can see that for low SNR values, the logarithmic term dominates. Thus, if increasing B decreases SNR (as is the case when we transition from a 20 MHz channel to a 40 MHz channel), there may be regimes where the capacity decreases (or is similar). In Fig. 1, we plot the theoretical capacity of both 20 MHz and 40 MHz channels. For each 20 MHz SNR value (as seen on the x-axis), the corresponding 40 MHz SNR is 3 dB less. It is seen that while the 40 MHz capacity is significantly higher for high SNR values, such capacity gains are not viable for low-SNR regimes. Note that this theoretical capacity assumes the existence of perfect encoding and error recovery mechanisms and is an optimistic upper bound on performance. The validity of these theoretical assessments in real settings has to be investigated, since the noise may not be AWGN and ideal encoding schemes do not exist in practice. While Shannon's equation gives an intuitive description, the experiments that we present next reveal that the practical performance does not exactly follow this theoretical assessment. The 40 MHz throughput in low-SNR regimes can be much worse than that of a 20 MHz channel.

Experimental validation: We use the WarpLab framework with WARP [5] hardware to implement a basic OFDM system. We generate a random bitstream and modulate it using DQPSK. The Inverse Fast Fourier Transform (IFFT) is applied on the modulated I - Q (In-phase and Quadrature) samples. A cyclic prefix is then added. A Barker sequence is later prepended to facilitate the symbol detection at the receiver. These samples are transmitted over the air using 2 x 2 STBC (Space Time Block Codes with two antennas - Alamouti) [21]; we use the STBC mode of transmission since on poor quality links, the auto-rate function of our 802.11n cards induces operations in this mode. At the receiver side, the preamble sequence is detected and stripped. The cyclic prefix is removed and the remaining samples are fed into a Fast Fourier Transform (FFT) module. After demodulating the samples, the receiver obtains the bitstream. We implement wide channels by appropriately changing the subcarrier mappings, sampling rate and using a 128-point FFT (as opposed to a 64-point FFT with a 20MHz channel).

First, we investigate the spectral characteristics of the transmitted waveform. We obtain the power spectral density (PSD) of the transmitted signals. The same power T_x, is used for both 20 and 40 MHz channels. PSD reflects the distribution of the energy with regards to the frequency content of the signal. Figure 2 depicts the PSD estimate with 56 and 114 subcarriers. It is evident that there is a 3dB reduction (from -92 dB to -95 dB) in the energy per subcarrier when we double the channel width. Note that in 802.11n, the central frequency F_c is not the same for 20 and 40 MHz channels (we deliberately plot the PSD using the same F_c for both bandwidths in Figure 2). In practice, when two 20 MHz channels (centered at F_{c1} and F_{c2} where $c1 < c2$) are merged together, the resulting channel is centered at $F_{c1} + 10$ [22].

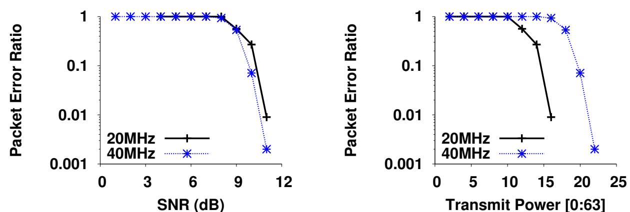
To elucidate the effects of wide channels on a received signal, we present a typical sample from the received QPSK constellations for both 20 and 40 MHz channels in Figure 3. With 20 MHz the received symbols are mostly clustered around the actual transmitted symbol on the I - Q plane. With wide channels, there is a higher uncertainty due to the lowered energy per subcarrier. The signals are more vulnerable to fading and more likely to be erroneously decoded. The higher baud error rate (error rate of QPSK symbols) results in a higher BER.

To look at the implications of our last observation, we measure the Bit Error Rate (BER) with 20 and 40 MHz channels. We use the OFDM reference design from [5]. On top of the OFDM PHY, we use the BERMAC implementation [5] to transmit packets and calculate the BER for various settings. We use a custom Java application that transmits back to back packets to an Ethernet switch using the *jpcap* API [23].



(a) SNR (QPSK) (b) T_x (QPSK) (c) T_x (BPSK & 16-QAM)

Fig. 4. BER for QPSK modulation with respect to SNR (a) and with respect to T_x (b - c). Transmit power is varied by changing the gain of the power amplifier, which is a 6-bit value in WARP (from 0 to 63) as indicated on the x-axis. For a given T_x, wide channels result in a higher BER (b and c).



(a) PER vs SNR (b) PER vs T_x

Fig. 5. Uncoded PER for QPSK modulation. As expected, the higher BER with wide channels results in a higher ratio of packet losses at the MAC.

The BERMAC implementation loads specific buffers of the WARP boards (on both the transmitter and the receiver boards) with the packet transmitted by the Java application; thus, the receiving node knows the *correct* payload contents for the BER calculation. In our experiments, we transmit a total of 9000 packets with a packet size of 1500 bytes and collect the BER statistics from the receiving board. We calculate the BERs using our WARP boards with 20 and 40 MHz channels, with QPSK. Note here that these are uncoded BERs (no forward error correction (FEC) employed at the PHY). The BER results with respect to the measured SNR are presented in Figure 4 (a). As one can expect, for a fixed SNR, the BER does not depend on the channel width. We also plot on the same figure the theoretical bit error rates for the considered system from [20]; the theoretical BER formula depends only on the SNR per subcarrier and not on the bandwidth. We observe that the experimental curves fit well with the theoretical plots [4]. In particular, the coefficient of determination [24] is 0.8 and 0.89 for 20 and 40 MHz, respectively. Figure 4 (b) presents the same set of BER measurements, but with respect to T_x. We notice that the wider channel exhibits a higher number of bits in error for a given T_x, thus corroborating our intuition (discussed earlier). We observe a similar BER increase with other modulations (see Fig. 4 (c)).

B. Effects of wide channels on higher layers

The PHY layer performance is not always directly exported to the higher layers (due to mechanisms such as FEC). Therefore, the performance degradation in terms of BER with a 40 MHz channel for a fixed transmission power, may or may not

[4]We leverage this later in designing ACORN in Section IV.

mod^{cod}	$QPSK^{3/4}$	$16QAM^{3/4}$	$64QAM^{3/4}$	$64QAM^{5/6}$
$\sigma \geq 2$	-7dB	3dB	5dB	8dB
$\sigma < 2$	-4dB	5dB	7dB	11dB

Fig. 6. Experimental transition table for σ values.

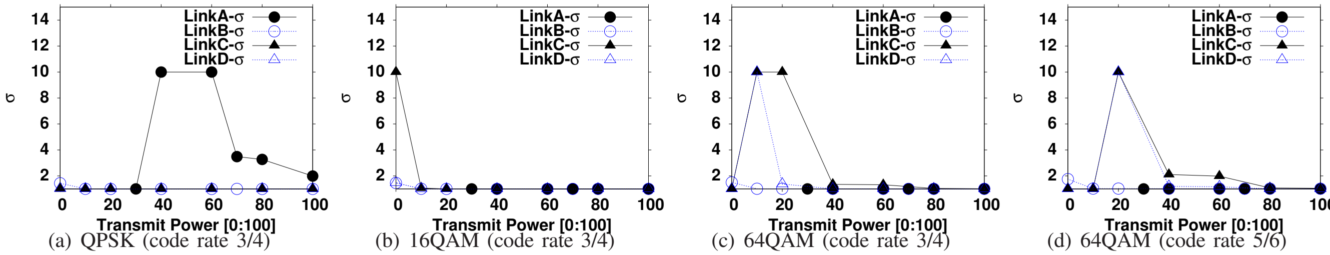
be reflected in the performance observed at the higher layers. To understand the effect at the packet level, we look at PER (Packet Error Rate). A small increase in the raw uncoded BER (when using a 40 MHz channel) might result in no change in the PER on a commercial coded system such as 802.11n. If so, the throughput enjoyed at the application layer is practically doubled (ignoring MAC overhead). On the contrary, if the PER is also increased, this will result in less than a two-fold increase in the throughput or in some cases, could even result in a throughput reduction. Assuming the throughput T with transmission rate R is roughly $T = (1 - PER) \cdot R$, the throughput with a 40 MHz channel will be lower than that with 20 MHz if the following holds:

$$\sigma = \frac{1 - PER_{20}}{1 - PER_{40}} > \frac{R_{40}}{R_{20}} \approx 2, \qquad (3)$$

where PER_x and R_x are the PER and the nominal transmission rate with the x MHz channels. Here, σ is simply the ratio of packet delivery probabilities achieved without and with wide channels.

PER performance: Using the previous experimental setup and results, we first obtain the uncoded PER. Figure 5(a) presents the PER with respect to the SNR. As discussed, for a given SNR the BER does not depend on the channel width; thus, the uncoded PER is similar for the 20 and 40 MHz channels *for the same SNR*. However, for the same T_x, the PER with wide channels is much higher as compared to that without the feature (as seen in Figure 5(b)). Recall that with a 40 MHz channel, for the same T_x, the SNR per subcarrier is halved and this contributes to the performance degradation.

Experiments with commodity 802.11n cards: To examine the performance with commodity systems employing FEC, we conduct experiments on our 802.11n testbed. Our testbed consists of 18, 2 x 3 802.11n nodes, each equipped with a Ralink mini-PCI wireless card and three 5-dBi omnidirectional antennas. The testbed contains both indoor and outdoor links [25]. We use the 5GHz band for our experiments, avoiding interference from other WLANs in the 2.4GHz band.



(a) QPSK (code rate 3/4) (b) 16QAM (code rate 3/4) (c) 64QAM (code rate 3/4) (d) 64QAM (code rate 5/6)

Fig. 7. σ-values for different links, T_x, modulations (mod) and code rates (cod). Transmit power is varied by changing the percentage of maximum power applied using the *iwpriv* utility (shown from 0 to 100 on the x-axis). For a given link, wide channels are beneficial ($\sigma < 2$) only beyond a certain power level. For lower power levels (lower SNR), wide channels hurt performance ($\sigma \geq 2$).

With our initial 802.11n experiments, we examine the performance of the PER with a coded PHY layer. We tune the transmission power on our links in order to account for a large set of SNR values, and we measure the PERs with both 20 and 40 MHz channels. In Figure 7, we plot the σ values (recall Eq. 3) for various modulation schemes and code rates for four representative links (we omit BPSK since it exhibits a similar performance as QPSK). Whenever σ is larger than 2, the throughput achieved with wide channels will be lower than that with a 20 MHz channel (Eq. 3). Figure 6 presents the observed SNR values (γ) when we have a *crossover* value of $\sigma = 2$. The common trend identified among all the cases where $\sigma \geq 2$ is that this degradation in performance is observed for a certain range of transmission powers. This region maps to a 2 - 3 dB difference in SNR [5]. More specifically, for low T_x, the PER for both the 20 and 40 MHz channels is similar (and close to 1), resulting in $\sigma \approx 1$. As we increase the power, the PER with a 20 MHz channel drops faster (with respect to T_x), since the SNR at the receiver is 3dB higher as compared to the case with wide channels. Thus $(1 - PER_{20})$ increases faster than $(1 - PER_{40})$ and the ratio σ can indeed assume values larger than 2; however, as we keep increasing T_x, the SNR with 40 MHz also increases and therefore, the PER performance with the two cases become similar to each other again (almost no packet losses) and $\sigma \approx 1$. Furthermore for a given link, the SNR value γ, at which we begin to see a PER decrease with 20 MHz (which results in $\sigma \geq 2$), is higher as the modulation becomes more aggressive (Figure 6). The reason for this is that with more aggressive modulations there is a higher SNR requirement to correctly receive packets.

Note that, for some robust links (e.g., link B in Fig. 7) the PER is extremely low for both the 20 and 40 MHz channels and here wide channels will provide significant benefits in terms of throughput. For poorer links, the difference in the PER performance can be significant and inequality 3 might be satisfied. In such cases, a 20 MHz channel is preferable.

Throughput performance: From the perspective of the end-user, the achievable throughput at the application layer is what is important. To examine the application layer performance, we measure the achievable throughput with and without wide channels on our 802.11n testbed. Note that, so far we have examined the impact of wide channels using a fixed modulation. However in practice, rate adaptation mechanisms can potentially cope with the reduced SNR due to wide channels by adaptively using a more robust Modulation Coding Scheme (MCS [1]). For this reason, we use the rate control algorithm of our wireless cards to assess the performance in the presence of rate adaptation and FEC. This proprietary algorithm not only adjusts the rates in response to packet successes / failures but also picks the best mode of operation (SDM or STBC) based on the channel quality. We consider both UDP and TCP traffic generated by the *iperf* tool. The maximum transmission power is used and we consider all of our links (24 in total) to capture a wide variety of link qualities. Figure 8 (a) depicts the results. We see that in about 20% of our experiments, the use of the conventional 20 MHz channel yields higher throughput. What is more interesting is that the majority of these cases are clustered in the low throughput regimes. In addition, the throughput gains are very significant in these regimes (the points in the lower left corner of Fig. 8(a)); for example, 20 MHz channels achieve 5 to 6 Mbps while 40 MHz channels yield almost 0 Mbps throughput. The SNR values observed during these experimental trials were less than 6dB, which conforms with our previous BER / PER observations in Figure 6. We observe that the rate adaptation mechanism does indeed lower the MCS to the most robust BPSK modulation. However, this is not sufficient to restore the throughput with wide channels for links with very low SNRs. In addition, approximately 30% of the TCP experiments yield better performance with 20 MHz as compared to only 10% with UDP. TCP is more sensitive to packet losses and as a result even a small PER increase due to wide channels can significantly degrade performance.

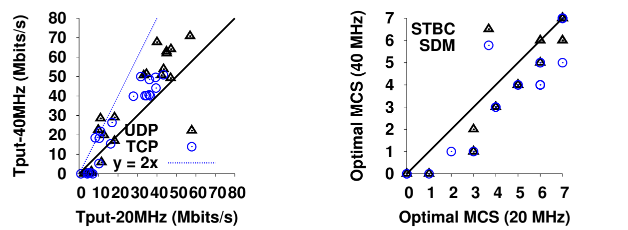


Fig. 8. Throughput experiments with rate control (left) and with fixed rates (right). Optimal MCS denotes the MCS giving the highest UDP throughput for a link. Wide channels primarily hurt performance for links with low SNRs even in the presence of rate control and FEC.

To understand the above observations, we next experiment with fixed transmission rates. For every link on our testbed, we find through exhaustive search, the MCS which gives the

[5] When σ is > 10, we cap its value at 10 for better visualization.

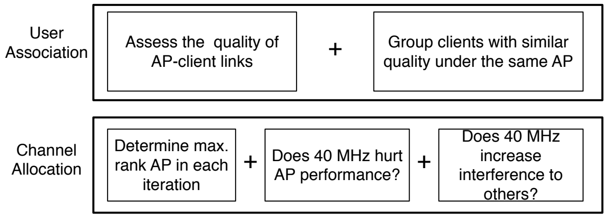


Fig. 9. High level functions of ACORN.

highest UDP throughput with and without wide channels, considering both modes of 802.11n (SDM and STBC). The results from Figure 8 (b) imply that the optimal modulation scheme with 40 MHz is almost always less 'aggressive' (i.e., smaller MCS) as compared with the one with 20 MHz. This results in less than a $2x$ throughput increase with wide channels as compared to 20 MHz channels. Figure 8 (a) verifies this, since the vast majority of the points lie on the right side of the line $y = 2x$. This is again an artifact of the increased BER and PER with wide channels.

To summarize, our experimental study shows that wide channels do not always increase throughput for links in isolation (such adverse effects of wide channels have not been reported in prior studies). If one were to also consider the increased interference from wide channels, it becomes evident that channel assignment should be carefully conducted for 802.11n WLANs. In addition, user association is even more critical in the case of 802.11n than in legacy 802.11 systems; a poor client might hurt the throughput of the other clients of a cell that utilizes wide channels. Next, we describe the design of ACORN, which accounts for all of the above factors.

IV. Harvesting ACORN

ACORN is designed based on the understanding developed with the experiments described in the previous section. It consists of two modules: (a) a user association module and (b) a channel assignment module that accounts for wide channels. The operations of ACORN, are briefly depicted in Figure 9. In short, the functions of the two modules are the following:

a) The **user association module** tries to group users (or clients) of similar link qualities within the same cell. The basis for this grouping is that the presence of a few poor quality users in a cell can degrade the performance drastically with 40 MHz bands. In such cases, even the good clients suffer due to the 802.11 performance anomaly [4]. In brief, the distributed coordination function (DCF) used in 802.11 ensures equal long-term medium access opportunities. Since poor clients occupy the channel for longer periods, the good clients are hurt as well. This effect would cause an AP with an associated poor client, to suffer from degraded throughput if it were to use wide channels. If instead it does not use wide channels, the potential throughput gains for high SNR client links are lost. To address this, ACORN tries to ensure that each cell either has (preferably) all users with high quality links, or contains larger numbers of users with poor link qualities. In the former case, the cell can use wide channels and in the latter it would simply use a 20 MHz channel.

b) The **channel allocation module** exploits the application of the user association module. It assigns 40 MHz channels to those APs that achieve the highest improvements in throughput (clearly these are the APs that contain the most clients with good quality links). 20 MHz channels are assigned to APs that either suffer degradations in throughput with 40 MHz channels (due to the presence of poor clients) or do not achieve significant gains with wide channels.

Note that many of the previously proposed WLAN configuration schemes minimize the total transmission delay [18], [19]; this achieves fairness among the users. However, our objective is to ***maximize the total network throughput***. In other words, we tradeoff some level of fairness for significant gains in the total network-wide throughput. This is the current trend in many commercial platforms (e.g., 3G / CDMA), which typically employ schedulers that give priority to high quality links (e.g., PF scheduler) [26], [27]; they maximize the total network throughput, allowing for some hit in terms of fairness across the users. In addition, many studies align with this direction (for example [28] and [29]). We assume saturated downlink traffic for analytical tractability of ACORN's decisions. Most of the previous work also relies on this assumption [19], [30]. However, we show experimentally that ACORN helps even with unsaturated loads (e.g., TCP).

A. User Association

A newly arriving client u usually has a set A_u, of serving APs to choose from. In order to pick the *best* AP for association, an objective must be in place. With ACORN, the decision is based on the pairing that achieves the maximum aggregate network throughput.

Gathering information for user association decisions: To achieve our goal, u needs to know for every AP $i \in A_u$ the per client throughput of i, with and without u associated with it ($X^i_{w,u}$ and $X^i_{wo,u}$, respectively). The client computes these values by obtaining a modified beacon. This beacon includes the number of clients associated with the AP (including u) K_i, the transmission delays per client d^i_{cl}, the aggregate transmission delay ATD_i of the AP and the channel access time M_i of the AP (if there is fully saturated traffic and no contention, $M_i = 1$). Client u calculates the above quantities as (i) $X^i_{w,u} = \frac{M_i}{ATD_i}$ and (ii) $X^i_{wo,u} = \frac{M_i}{ATD_i - d^i_u}$ [18].

In order for the AP to be able to include these information in the beacon, the user has first to associate with it. Other, more simplistic approaches for AP selection, do not require prior client association with the APs. For example, affiliation decisions that are based on the received signal strength (RSS) of the beacons, do not require each user to associate with the APs in range first. However, it is shown that cross layer information is important for user affiliation to deliver good performance [30]; for instance simply looking at the RSS can lead to configurations with a few overloaded APs and other underloaded APs. In order to obtain the required information accurately, a user needs to associate with the AP and exchange traffic. Thus, we implement a similar approach to the one proposed in [18] [19] to obtain the information required by our algorithm. Note however that with ACORN the decision on which AP to affiliate with, is different.

V	Set of Access Points
Ch	Set of available 20 and 40 MHz channels
$F : V \rightarrow Ch$	Channel assignment mapping
f_i	channel assigned at AP i
X_i	Throughput of AP i

TABLE I
NOTATIONS FOR CHANNEL ALLOCATION ALGORITHM.

Associating with an AP: Based on the information gathered from all the APs in range, u picks the AP $i^* \in A_u$, which maximizes the following utility function with respect to i:

$$U_{asoc}(u,i) = K_i \cdot X^i_{w,u} + \sum_{j \in A_u, j \neq i} (K_j - 1) \cdot X^j_{wo,u} \quad (4)$$

The first term on the right hand side of Eq. 4 is the total throughput of the AP with which, u associates. The second term is equal to the total throughput achieved by the other APs in the range of u. Note here that K_j was defined as the number of clients associated with AP j, including client u. When a new client joins the cell, there may be a reduction in throughput due to the increased transmission delay. The goal is to minimize this reduction and preferably maintain the throughput at the level prior to the client's arrival. Eq. 4 minimizes the impact of a poor client v, in the network. v affiliates with an AP serving similar quality clients, since this will minimize the total network throughput degradation (i.e., maximize the total network throughput) that could result from the 802.11 performance anomaly [4]. Clients with high quality links do not significantly affect the throughputs due to the anomaly when they associate with their best APs. The pseudocode for user association is given in Algorithm 1.

Algorithm 1 User Association Algorithm

```
Input: K_i, M_i, ATD_i, ∀i ∈ A_u and d^i_v ∀i's clients
Output: AP i that client u associates with

for i ∈ A_u do
    X^i_{w,u} = M_i / ATD_i
    X^i_{wo,u} = M_i / (ATD_i − d^i_u)
    U_asoc(u,i) = K_i · X^i_{w,u} + Σ_{j∈A_u, j≠i} (K_j − 1) · X^j_{wo,u}
end for
return i* : U_asoc(u,i*) ≥ U_asoc(u,i), ∀i ∈ A_u
```

B. Wide Channels Decision/Allocation

Next, we describe the channel allocation module of ACORN. Table I enlists the notation used.

Problem Formulation: The channel allocation problem is cast as a graph coloring problem [15]. We apply the idea of the *interference graph (IG)* (as in [14], [15]). The set V of vertices of the interference graph $G(V,E)$ are the APs. An edge $e_{ij} \in E$, if APs i and j interfere with each other. In the classic graph coloring problem [31], the objective is to assign colors from a given set of colors to the vertices of the IG, such that no adjacent vertices have the same color. Note here that, the notion of *color conflicts* differs in our case due to wide channels. For instance, let us assume colors c_i and c_j, corresponding to channels f_i and f_j (20 MHz channels). Then the *composite color* $\{c_i, c_j\}$ corresponds to the 40 MHz channel derived from the combination of f_i and f_j. With this set up, the basic colors c_i and c_j do not conflict; however, each of them conflicts with the composite color $\{c_i, c_j\}$. In the rest of the paper we will refer to both basic and composite colors simply as colors. We relax the constraint of the above graph coloring problem, since our objective is to assign colors to the vertices (i.e., channels to the APs), so as to maximize the total network throughput. Formally, we seek to:

$$\max_F \quad Y = \sum_{i \in V} X_i(F) \quad (5)$$

NP-completeness: The graph coloring problem with the above objective is NP-complete. The classic, NP-complete, **decision graph coloring problem** [31], tries to answer the following: "Given a graph $G(V,E)$ and k colors, can we color the vertices V such that $\forall e_{ij} \in E \rightarrow f_i \neq f_j$?", where f_i is the channel assigned to AP i.

The total aggregate network throughput Y, is upper bounded by $Y^* = \sum_{i \in V} X^{isol}_i$, where $X^{isol}_i = \max\{X^{isol-20}_i, X^{isol-40}_i\}$ is the maximum possible throughput for AP i in an interference-free setting, achieved with either a 20 or a 40 MHz channel. Let F' be a solution to our problem, yielding a total aggregate network throughput of Y'. The solution is optimal **iff** $Y' = Y^* \Leftrightarrow G$ has a k-coloring. Thus, our problem is NP-complete.

Our approach: We design an algorithm that allows APs to decide upon the channel(s) to use. Later, we compute the approximation ratio of our algorithm relative to the optimal. Initially, all APs are assigned either a 20 MHz or a 40 MHz channel at random. The algorithm is iterative and executed with a periodicity of T. In every iteration, the AP that can provide the maximum increase in the aggregate throughput by switching channels, is allowed to switch. The algorithm terminates, after a number of iterations K, either when no further improvement can be provided or when the improvements provided are very small. A pseudocode for our algorithm is given in Algorithm 2. Y^W_x represents the long-term aggregate network throughput achieved at period W and after x iterations of the algorithm.

In each iteration of the algorithm, the APs that have still not chosen new channel(s) (i.e., members of the set AP), estimate the aggregate throughput achieved with every possible channel, assuming that other APs keep their current allocation (line 10).

Estimating throughput: In order to estimate the throughput on a new channel, an AP needs to take into account (i) the number of APs already residing on this new channel and (ii) the quality of the links to its clients on the channel. The first requirement is possible either with help from an administrative authority or the Inter Access Point Protocol (IAPP) [32]. For the second requirement, we assume that the link quality on the different channels (of the same width) is not significantly different. Later in this section, we provide measurements that validate this assumption in indoor slowly varying settings, typical for enterprise 802.11n WLANs. However, this assumption does not hold when channels are of different width. In other words, the channel qualities to the clients may change if a channel of different width is used. To map the measured results

Algorithm 2 Wide Channels Selection Algorithm

1: **Input:** Y_k^{T-1}, F^{T-1}
2: **Output:** F^T
3: $Y_0^T = Y_k^{T-1}$, $k = 0$
4: **repeat**
5: $label \quad (1)$
6: $AP = V,\ AP^{'} = \emptyset$
7: **for** $i \in V$ **do**
8: $k = k + 1$
9: **for** $c \in Ch$ **do**
10: $Tmp_i(c) = \sum_{a \in V} X_a(F^T_{j \in AP'}, f_i = c, F^{T-1}_{j \in AP})$
11: **end for**
12: $pick \quad c_i^* : Tmp_i(c_i^*) \geq Tmp_i(c), \forall c \in Ch$
13: $rank_i = Tmp_i(c_i^*) - Y_{k-1}$
14: **if** $\max_{i \in V} rank_i < 0$ **then**
15: **if** $|AP^{'}| \leq 1$ **then**
16: ***return*** $F = (F^{T-1}_{j \in V}, F^T_{j \in V})$
17: **else**
18: $GOTO\ (1)$
19: **end if**
20: **else**
21: $\text{“}winner\text{”}\ is\ AP\ m : rank_m \geq rank_n, \forall n \in V$
22: $f_m^T = c_i^*, AP = AP/\{m\}, AP^{'} = AP^{'} \bigcup \{m\}$
23: $Y_k^T = \sum_{a \in V} X_a(F^{T-1}_{j \in V}, F^T_{j \in V})$
24: **end if**
25: **end for**
26: **if** $AP \neq \emptyset$ **then**
27: $GOTO \quad (1)$
28: **end if**
29: **until** $Y_k^T < \epsilon \cdot Y_{k-1}^T$

from a 20 MHz channel on to a 40 MHz channel (or vice versa), we leverage the understanding obtained from our PHY layer measurements in Section III.

We estimate the link quality on a channel of different width as follows. The input is the SNR at the current width. When we change the width (from 20 to 40 MHz and vice versa), there is a 3dB change in the SNR; this processing is performed by a *SNR calibration* module in our estimator. Using this calibrated SNR value, a *BER estimation* module calculates the theoretical coded BER (from [20]). Recall, from our measurements that one can expect a reasonable match between the values computed with the theoretical formulas in [20] and the experimentally observed BER.

Finally, using BER we estimate PER. We use the commonly used assumption (e.g., in [33]) of independent, uniformly distributed bit errors within a packet and compute PER as:

$$PER = 1 - (1 - BER)^L. \tag{6}$$

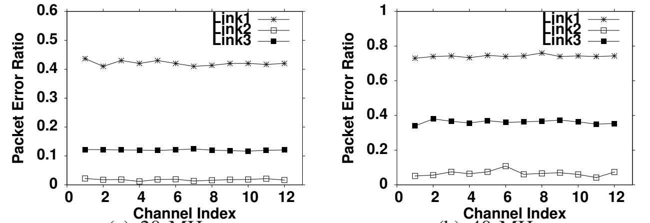
Note here that ACORN does not require the exact BER or PER values; it only needs a coarse estimate of the link quality i.e., a reasonable classification of good and poor links.

Once the performance on each of the available channels is estimated, the AP that can provide the maximum increase in the aggregate throughput by switching channels does so. This approach in essence, mimics the gradient descent algorithm; it greedily seeks to find the point that exhibits the maximum increase in the value of the objective function (the throughput).

The same procedure is repeated considering the APs that have not had an opportunity to switch. When no improvement is possible or the improvement is incremental (ϵ - line 29), the algorithm stops. In our implementation, $\epsilon = 1.05$ (i.e., if there is a 5% or less increase in the total aggregate throughput as compared to the previous iteration, the algorithm stops).

Approximation Ratio: Gradient-based optimization can be trapped in a local extremum. Given also that the channel allocation problem is NP-complete, we are interested in finding the worst case approximation ratio of our algorithm.

The maximum possible aggregate throughput is obtained when all APs operate in an interference-free setting, and is equal to: $Y^* = \sum_{i \in V} X_i^{isol}$ as mentioned before. The worst local extremum where our algorithm can be trapped, is the one in which every AP uses the same (20 or 40 MHz) channel. In other words, nodes are not just assigned conflicting colors, but are assigned exactly the same color. This is because, if they are assigned different conflicting colors (a composite color and a basic color) the achieved throughput will be higher (this is easy to verify). In this case, the throughput of every AP u will be reduced by a factor of $\frac{1}{deg_u + 1}$, assuming fully saturated traffic, where deg_u is the degree of node u[6]. Consequently the long-term total network throughput will be $Y_{worst} = \sum_{i \in V} \frac{1}{deg_i + 1} \cdot X_i^{isol} \leq \frac{1}{\Delta + 1} \cdot \sum_{i \in V} X_i^{isol}$, where Δ is the maximum node degree in the network. Thus, our algorithm has a worst case approximation ratio of $O(\frac{1}{\Delta+1})$. As shown in Section V, in practice, the channel allocation scheme performs much better.



(a) 20 MHz (b) 40 MHz

Fig. 10. Link quality on different channels (without interference) does not exhibit significant differences.

Link quality on different channels: We assume that the quality of a link does not exhibit significant variations in terms of PER on different channels of the same width. To verify this, we conduct the following experiment. For all the links, we measure back-to-back, the PER on the different channels, using the maximum modulation of 64-QAM (MCS = 15 [1]). Figure 10 presents the results from three representative links. Our measurements demonstrate that, indeed, the

[6]Note here that, the graph we consider is the interference graph of the network [15] with respect to the APs (vertices of the graph). Two APs interfere with each other either if they directly compete for the medium or if either competes with at least one of the other AP's clients.

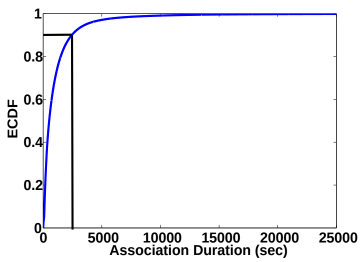


Fig. 11. CDF of user association durations.

variations across the different channels are negligible (for both 20 and 40 MHz channels), making our assumption realistic. Note that since the results in Fig. 10 are with the most aggressive modulation (i.e., 64-QAM), the PER variations are even smaller for other less aggressive modulations. There are studies (e.g., [8]), that have reported variations in the link quality with different channels. However, these studies are on single antenna systems. In contrast, in our experiments, we utilize the MIMO PHY of 802.11n. The use of MIMO makes the performance stable and decreases variations across the different channels (arising primarily due to fading in single antenna systems). ACORN can easily be modified, such that each AP scans (one at a time) all the available channels and gets more accurate information regarding the link quality to its clients. However, this would add more complexity and increase the convergence time of the system.

Periodicity of our algorithm: The periodicity T with which we apply channel allocation needs to be carefully chosen. If we apply it too often, then the hit in the throughput could be significant due to the overhead. If on the other hand, we activate channel allocation too infrequently, the topology might have significantly changed in the interim and the current allocation might provide poor performance.

In order to assess this tradeoff, we use data collected from 206 different (commercial) APs, in a time period spanning more than 3 years from the CRAWDAD repository [34]. In particular, we extract the association duration of each user. Figure 11 depicts the CDF of the association duration. More than 90% of the associations last less than 40 minutes and the median is approximately 31 minutes. Based on these data, we run our channel allocation algorithm every 30 minutes.

C. ACORN and Other Rate Adaptation Algorithms

In our discussion, we have so far assumed that if an AP is configured with a particular channel width (whether 20 MHz or 40 MHz), that channel width is used for all of AP's clients. Our results in Section V also reflect this assumption since the Ralink RT2880 APs use a fixed channel width for all of their clients. However, other commercial 802.11n drivers such as *ath9k* [35] can adjust the channel width while performing rate adaptation for each AP-client link. In other words, such drivers can both adapt channel width and the modulation on a per packet basis. Next, we discuss how ACORN's functionality relates to such rate adaptation capabilities.

User Association: Recall that when a new user u arrives, it joins an AP i based on the per client throughput of i, with and without u associated with it ($X^i_{w,u}$ and $X^i_{wo,u}$, respectively). We assumed that when computing $X^i_{w,u}$, u factors in the delay of its link to AP i based on i's current fixed channel width and the resulting MCS for the link between u and i. For the case where AP i can adjust its channel width for each of its clients, u simply needs to determine the best channel width (and the resulting MCS) for its link to i, when it computes $X^i_{w,u}$. Despite this small modification, the user association objective still remains the same as expressed in Eq. 4.

Channel Allocation: A single AP that has the above-mentioned rate adaptation capabilities can potentially achieve ACORN's objective with respect to intelligent use of wide channels. Here, properly alternating the channel width would allow such an AP to address the bottleneck effect of low-SINR clients (by using 20 MHz for them) and at the same time to serve high-SINR clients with 40 MHz. However, the long-term throughput of the cell in this case would only be similar to (or may be marginally higher than) ACORN, since the bottleneck effect is still present and is addressed in the same way as ACORN would address it (e.g., using 20 MHz).

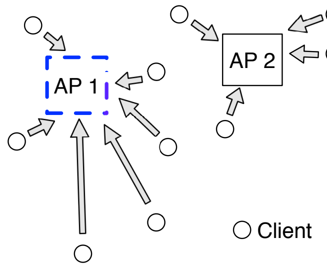
When there is more than one AP, there are two possibilities. First, there may be enough number of channels such that each AP can use orthogonal wide channels. In this case, the same performance can be achieved without the need for ACORN (similar to the above single AP case). However, when there are not enough channels to achieve complete isolation, ACORN can provide significant gains and we describe why this is the case with the following example.

Let us assume that there are only three adjacent orthogonal channels (i.e., one wide channel consisting of two adjacent channels and one regular channel) and two interfering APs. Here, only one AP can would use the wide channel to achieve complete isolation. While the AP with the wide channel can alternate between 20 MHz and 40 MHz, the other AP would be limited to 20 MHz for all of its clients (even though it is capable of adjusting the channel width per client). Here, it is important to identify which AP should be granted the wide channel and ACORN can address this by its greedy, iterative selection based on the long-term throughput offered by each AP. As an example, one of the APs (say AP A) may have more clients that can benefit from the wide channels and very few clients that are better with a 20 MHz channel. Conversely, the other AP (say AP B) may have more client links that would warrant the use of 20 MHz, and very few high-SINR clients that benefit from wide channel. In this case, ACORN would assign the wide channel to AP A and provide higher throughput than the case when only AP B would use the wide channel [7].

V. Evaluating ACORN

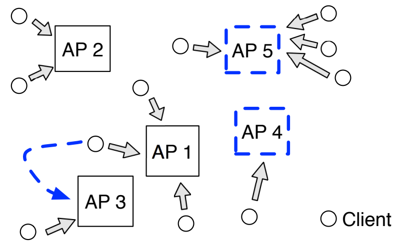
In this section, we detail the implementation of ACORN and its evaluation using our 802.11n WLAN testbed.

[7]While allowing both APs to opportunistically use the wide channel is certainly possible, this would inevitably result in collisions and thus, is not considered in our discussion.



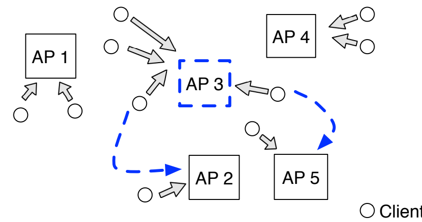
	AP 1	AP 2	Total (Mbps)
ACORN (Tput)	16.03	52.9	68.93
[18] (Tput)	3.15	53.1	56.25

(a) Topology 1



	AP 1	AP 2	AP 3	AP 4	AP 5	Total (Mbps)
ACORN (Tput)	56.6	53.5	56.3	3.78	15.9	186.08
[18] (Tput)	55.8	54.1	20.4	0.56	6.35	137.21

(b) Topology 2



	AP 1	AP 2	AP 3	AP 4	AP 5	Total (Mbps)
ACORN (Tput)	64.2	52.5	11.4	57	44.9	230
[18] (Tput)	64.3	35.3	1.09	57.7	42.4	200.79

(c) Topology 3

Fig. 12. ACORN can provide throughput gains in interference-free deployments. Solid arrows depict the association relationship between clients and APs. Dashed APs use 20 MHz with ACORN and 40 MHz otherwise. Dashed arrows depict the different user affiliation decisions taken by [18].

A. Implementation Details

We implement our algorithms using the Click modular router (v1.6) [36]. We implement a user-level utility that runs both at the APs and the clients. We keep track of the SNR, the nominal rate and the association time per client by using the functions implemented in our card's driver. The delay for each client is calculated and broadcast in a beacon as described in Section IV, along with the M_a values (defined in Section IV-A), the number of clients and the aggregate transmission delay of an AP. The client receives the beacons from every AP in range and makes appropriate association decisions.

Calculating per client transmission delay and M_a: These metrics are not directly available since our hardware does not provide access to firmware. We implement a module where every AP calculates the delay of a client by utilizing our PER estimation procedure and the nominal rate for the client. We *estimate* M_a for an AP a by $\frac{1}{|con_a|+1}$ where con_a denotes the set of neighboring APs that reside on the same channel as AP a. This estimation has very high accuracy when these APs can hear each other under saturated traffic. Accurate management and configuration of WLANs is of most interest in these regimes i.e., in dense deployments and with heavy loads.

B. Experimental Evaluations

Comparison with legacy 802.11 WLAN configuration systems: We start by randomly assigning initial channels to APs from the 5GHz band. Clients are then randomly activated one by one. Each client performs user association (i) as per **Algorithm 1** or, (ii) the algorithm described in [18]. The APs then perform channel selection either as per **Algorithm 2** or a modified version of [18]. We modify the frequency selection algorithm in [18] to implement a greedy strategy where APs aggressively use the (single width) 40 MHz channels[8]. Specifically, they scan 40 MHz channels and select the one that minimizes the total noise and interference. We simply refer to this scheme as "[18]".

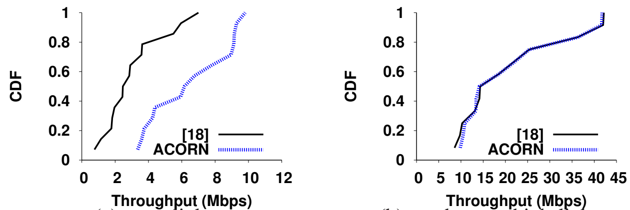
[8]As one might expect, simply using the algorithm with 20 MHz channels results in lower rates and correspondingly lower throughput. For clarity and ease of discussion, we omit these results here.

ACORN significantly improves per-cell throughput in interference free settings: In these experiments, we have saturated downlink UDP traffic (generated using *iperf*) from each AP to its clients. We evaluate ACORN on many different WLAN topologies. We employ all the twelve 20 MHz channels available in the 5GHz band with both ACORN and [18]. Figure 12 quantifies our per-AP throughput observations with a few sample topologies (also depicted). Topology 1 consists of 2 APs. This is a sparse WLAN where clients are connected with poor quality links with AP1 and good clients are associated with AP 2. We find that the user association with both ACORN and with [18] are identical. However, the use of the 20 MHz band provides a significant increase (*4x* throughput increase) for AP 1 because of its low-SNR client links. In fact, with the 3 dB reduction in SNR, we observe that the poor clients can hardly communicate with the AP when it uses wide channels with [18].

Topology 2 includes 5 APs. We observe that with ACORN, when poor clients associate with an AP, the AP uses a 20 MHz channel. The same APs use wide channels greedily with [18]. The presence of poor clients reduces the cell throughput of the corresponding AP. These effects are seen with AP 4 and AP 5 of the topology and for these, ACORN provides significant throughput improvements (*6x* for AP 4 and *1.5x* for AP 5). We also observe that ACORN results in different user associations for APs 1 and 3; as discussed, ACORN tries to *group* clients with similar link qualities in the same cell. In contrast, [18] evenly divides the clients between these APs regardless of the specific client link qualities. Due to this, AP 3 achieves a higher throughput (1.8x) with ACORN since it serves only one good quality client. This results in more congestion at AP 1 with ACORN as compared to [18] since it has to serve more clients. However, interestingly, AP 1 can still achieve the *same total throughput with more clients*. We identify the reason behind this to be the following: since ACORN groups similar-quality clients in one cell, the aggregate throughput does not change despite the fact that *per-client* throughput is reduced; the performance anomaly of 802.11 does not take effect. Similar performance gains are also observed in Topology 3. Here AP 3 achieves a $\approx$*10x* increase when it

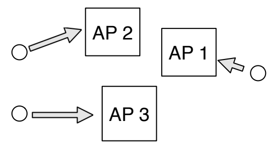
	ACORN	Random Configurations (Descending order)
Network Tput (UDP - iperf)	259.2	201.63, 193.1, 188.56, 187.6, 184.62, 183.39, 169.62, 163.32, 160.47, 159.35
Network Tput (TCP - iperf)	178.93	161.7, 155.77, 134.78, 133.4, 130.64, 114.1, 109.4, 106.6, 103.41, 102.3

TABLE II
ACORN ACHIEVES THE HIGHEST NETWORK THROUGHPUT (IN MBPS) AGAINST 10 BEST (OUT OF 50) MANUAL CONFIGURATIONS.



(a) poor links (b) moderate - high links

Fig. 13. ACORN improves the median HTTP file transfer throughput by *1.5x* for poor quality links (left) while retaining the performance of good quality links (right).



X,Y,Z	40,40,40	40,20,20 (ACORN)	20,40,20	20,20,40
Tput (Mbps)	42.3	79.98	54.15	52.38

Fig. 14. ACORN provides the highest throughput in settings with interference. X, Y and Z denote the channel widths (in MHz) used by APs 1, 2 and 3, respectively.

avoids wide channels with ACORN. We again observe that ACORN chooses to group similar quality clients around AP 3, instead of balancing the load across the APs. As a result of this grouping, AP 2 with ACORN also achieves higher throughput since it serves a single good quality client. We observe a similar behavior with ACORN in a variety of other scenarios.

In addition to downlink UDP traffic, we evaluate ACORN against [18] with a HTTP workload. In these experiments, we configure the APs as HTTP servers hosting files. The clients download a file from their APs and we measure the throughput of the file transfer (using *wget* [37]). Fig. 13 plots the CDF of the file transfer throughputs of each AP. For clarity, we plot the results separately for two categories of links: a) links that achieve $<$ 8 Mbps throughput with [18] (i.e., poor links) and b) links with $\geq$ 8 Mbps throughput with [18] (i.e., moderate and high quality links). While maintaining a similar performance for cells with good client link qualities, ACORN provides significant gains for cells with poor clients. For such clients, ACORN increases the median HTTP throughput by *1.5x*. These experiments demonstrate that the application throughput of clients also improves with ACORN for typical realistic traffic types.

ACORN reduces interference: In dense deployments where channel availability is limited, ACORN reduces interference at the neighboring APs and provides even higher improvements in throughput. To show this, we experiment with a representative scenario in Figure 14 where the number of APs is not small relative to the number of available channels (unlike in the previous experiments). We have 3 APs that contend for channel access and there are four 20 MHz channels made available. AP 1 serves a good quality client and APs 2 and 3 have poor clients associated with them. When all the APs aggressively use wide channels, they project interference on each other. In addition, APs 2 and 3 suffer because of the poor client links. Note that, with 4 channels, only one AP can use wide channels to achieve complete isolation. In such cases, it is essential for a channel allocation scheme to identify the best AP that should exclusively use wide channels. We observe that, ACORN identifies this AP and provides the highest throughput as compared to other possible allocations. It provides an almost *2x* improvement over the scheme that aggressively allows every AP to use wide channels; the aggressive allocation causes increased interference and thus, lower throughput.

Comparison with random manual configurations: We compare ACORN against a large set of manual configurations in terms of assigned channels and user associations. The purpose of this experiment is to see the effectiveness of ACORN in yielding the highest network throughput. In this experiment (different from previous experiments), we measure the performance in terms of both UDP and TCP throughputs (both generated by *iperf*). The experiments evaluate ACORN's performance with unsaturated TCP traffic; since our analysis assumes saturated traffic, we wish to examine if ACORN works well with unsaturated traffic as well. Note that, we are mainly interested in scenarios that fully load the network (saturated conditions), since achieving balance and efficacy is most important in these regimes. However, these experiments (together with the HTTP workload evaluation) demonstrate the applicability of ACORN in more generic settings.

For a randomly picked topology, we first run ACORN and obtain the total network throughput. Next, we configure APs with random channels (both 20 and 40 MHz) and let each client associate with one of the APs in range with equal probability. We repeat this experiment for 50 different configurations and take the 10 best configurations. Table II tabulates our results. We observe that ACORN configures the network in a way that achieves the highest possible throughput as compared to what is achieved with these random configurations. We wish to point out that ACORN provides gains with TCP since congestion can still occur at shorter time scales; at such times, the use of ACORN provides benefits. The decisions relating to wide channels deliver higher performance since they are based on client link qualities and independent of the type of traffic. Although the set of random configurations is by no means exhaustive, the experiments do demonstrate the efficacy of ACORN in terms of yielding high throughputs.

How close to the optimal is ACORN channel allocation

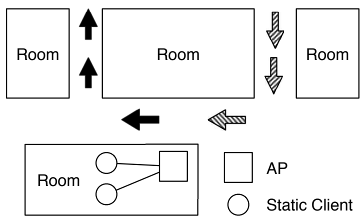


Fig. 16. Trajectory of our mobile client .

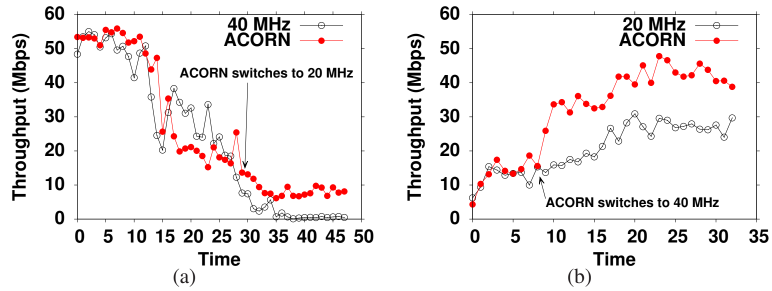


Fig. 17. ACORN tracks the link quality and selects the channel width that gives the higher throughput over fixed channel widths.

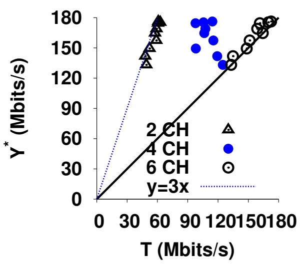


Fig. 15. ACORN has approximation ratios better than $O(\frac{1}{\Delta+1})$ in practice.

in practice?: Next, we perform experiments to examine the approximation ratios achieved by the ACORN channel allocation module in practice. We choose 3 APs that *compete* for channel access in each experiment (i.e., $\Delta = 2$); 9 such sets of different APs are considered. We then associate clients with each of these APs. We then run saturated UDP downlink traffic from each AP to its clients in *isolation* for both 20 MHz and 40 MHz channels. We calculate Y^*, which is the best possible aggregate throughput, as $\sum_{i=1,2,3} max(T^i_{20}, T^i_{40})$, where T^i_x is the throughput obtained by AP i using a channel width of x MHz. Note here that this maximum is achieved when we completely isolate the 3 competing APs i.e., they do not contend with each other. Subsequently, we run the ACORN channel allocation algorithm with 2, 4 and 6 orthogonal channels made available. Note here that, 6 orthogonal channels are enough for all of the APs to simultaneously use wide channels. Figure 15 depicts the total network throughput, T, obtained by ACORN in comparison with Y^*. Note that Y^* computed as above, is a *loose* upper bound, since complete isolation of the 3 APs is not always possible with less than 6 orthogonal channels. With 2 channels, ACORN does not perform worse than what is theoretically predicted; the aggregate network throughput is $\frac{Y^*}{3}$, since the medium access is shared among the contending APs. In the case of 6 channels, ACORN can achieve Y^*, since channel allocation isolates every AP and configures the best channel width for each AP. We observe some cases where ACORN performs very close to the optimal (what is possible with 6 channels) even with only 4 channels. Examining the cases with care, we find that there is at least one AP i such that $T^i_{20} > T^i_{40}$; ACORN accounts for this and configures the particular AP with a 20 MHz channel, leaving 3 channels for utilization to the other two APs.

Evaluating ACORN with mobility: With ACORN, once an AP is assigned a 40 MHz channel, it can opportunistically use its allocated channels. In other words, the AP can opt out from using wide channels and only employ the 20 MHz channel (one of the two assigned). Since the other APs choose their frequencies based on the channels assigned to this particular AP, using either of the two 20 MHz channels will not change the interference on the neighboring APs. This mode of operation is particularly desirable in WLANs with mobile clients. Since an AP to client link quality can vary temporally, the AP can dynamically activate the desired width of operation (20 vs 40 MHz) with ACORN based on the measured link qualities of its clients. We experiment with a scenario that involves pedestrian mobility. We configure a laptop with the same card that we use in our testbed and use it as a mobile client. In this experiment, we have a single AP that has 2 static clients in addition to the laptop. First, we position the laptop close to the AP and start moving it *away* from the AP. Figure 16 depicts this trajectory with dark arrows.The AP transmits downlink UDP traffic to its clients and we record the aggregate throughput measured as a function of time. Figure 17(a) presents the time trace of the aggregate cell throughput during the mobile client's movement. We compare ACORN against a configuration that strictly uses a 40 MHz channel. We observe that ACORN uses the 40 MHz channel in the beginning and sustains this until the point where the link quality becomes poor for the mobile laptop (around 30 sec). From that point until the end of the experiment (the client stops at a location far from the AP), ACORN falls back to the 20 MHz mode and is able to sustain a cell throughput that is almost ten times that of a fixed 40 MHz channel. Note here that the poor quality link to the distant client affects the good clients as well due to the 802.11 performance anomaly [4]. In a similar experiment, we have our client moving *towards* the AP, the trajectory is depicted with striped arrows in Figure 16. We compare ACORN against a fixed 20 MHz configuration. We observe that ACORN uses the 20 MHz until it recognizes the improvement in link quality (SNR); at that time it switches to a 40 MHz channel (at around 10 sec) and is able to utilize the gains from wide channels.

VI. Scope of ACORN

In our experiments, we evaluate ACORN in an enterprise setting where clients choose their AP from a set of candidate APs. In addition, user association and channel allocation are executed cooperatively so as to maximize the aggregate

WLAN throughput. In residential settings, the clients typically have only one AP to choose from and neighboring APs may not cooperate towards a common performance optimization. ACORN's benefits from user association will not be viable in such settings. However, ACORN can still be deployed with only the channel allocation component. Residential APs often have multiple clients due to the proliferation of mobile devices and wireless home entertainment systems. In such cases, it is important to prevent throughput degradation due to poor quality client links, by carefully applying wide channels. As previously shown, ACORN provides significant gains from intelligent application of wide channels and thus, can be deployed for residential settings as well. However note that, these gains from ACORN will only be significant if the hardware supports a fixed channel width. When APs are capable of adjusting the channel width for each client link, they can alleviate the performance degradation due to poor quality links without ACORN.

VII. Conclusions

The wide channels feature allows 802.11n nodes to use a wider frequency band towards achieving high data rates. We show that wide channels have associated caveats and may degrade performance even in interference-free settings. We conduct extensive experiments to understand why this is the case. Based on the understanding gained, we design and implement ACORN, an auto-configuration framework for 802.11n WLANs. We show via extensive evaluations that ACORN provides significant per-AP throughput gains (as high as 6x) over what is achieved with prior approaches designed for legacy 802.11 systems that are based on using single channel widths. To the best of our knowledge, ACORN is not only the first system to consider the application of wide channels in 802.11n WLANs but also the first system to consider the use of two distinct channel widths while performing joint channel allocation and user association.

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