Adjacent Channel Interference in 802.11a Is Harmful: Testbed Validation of a Simple Quantification Model

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ABSTRACT

Wireless LAN radio interfaces based on the IEEE 802.11a standard have lately found widespread use in many wireless applications. A key reason for this was that although the predecessor, IEEE 802.11b/g, had a poor channelization scheme, which resulted in strangling adjacent channel interference (ACI), 802.11a was widely believed to be ACI-free due to a better channelization combined with OFDM transmission. We show that this is not the case. ACI does exist in 802.11a, and we can quantify its magnitude and predict its results. For this, we present minor modifications of a simple model originally introduced by [1] that allow us to calculate bounding values of the 802.11a ACI, which can be used in link budget calculations. Using a laboratory testbed, we verify the estimations of the model, performing experiments designed to isolate the affected 802.11 mechanisms. This isolation was enabled by not using the wireless medium, and emulating it over cables and attenuators. Our results show clear throughput degradation because of ACI in 802.11a, the magnitude of which depends on the interfering data rates, packet sizes, and utilization of the medium.

INTRODUCTION

The IEEE 802.11a standard amendment describes an OFDM-based physical layer for 802.11 wireless stations operation in the 5 GHz band. Due to the poor channelization of 802.11b/g that left only three of the available channels non-overlapping, the channelization scheme of 802.11a was over-advertised to offer 19 non-overlapping channels in the European Telecommunications Standards Institute (ETSI) regulatory domain and 20 in the Federal Communications Commission (FCC) domain. This implied that no adjacent channel interference (ACI) was to be expected in 802.11a, and therefore no performance degradation would be observed for neighboring links operating in neighboring channels. Indeed, the 52 orthogonal frequency-division multiplexing (OFDM) subcarriers defined in the 802.11a amendment appear to lie well within the channel bandwidth of 20 MHz, and each channel's central frequency has a spacing of 20 MHz from the next/previous adjacent channel. Still, examining the transmit spectral mask[1] required for compliance in the specification [2], we see that some transmitted power is allowed to leak not only to the immediately adjacent channels, but also as far as two channels away from the communication channel.

Meanwhile, the wireless network research community endorsed 802.11a as the standard of choice for multiradio nodes and dense wireless LAN (WLAN) deployments. Two main reasons were behind this: First the 2.4 GHz band had been already overcrowded as the 802.11b/g compliant devices had been in the market long before the 802.11a ones and second because it was widely believed that 5 GHz capacity problems due to interference would be mitigated by the *non-overlapping* channels promised by the standard and the vendors. Unfortunately, although the power allowed to leak into the neighboring channels is indeed quite low compared to the transmitted signal power, it is sufficient to cause ACI effects, especially when neighboring radio interfaces use nearby channels, or when the signal-to-interference-plus-noise ratio (SINR) observed at the receiver of node is marginally larger than the threshold required to support a required rate.

RELATED WORK

The authors of [3] performed experiments on a testbed with Atheros-based 802.11a interfaces to examine the effect of potential ACI on a dual-radio multihop network. Their work includes both laboratory and outdoor experiments using omnidirectional antennas. The former indicated that the Atheros AR5213A-chipset interfaces they employed were indeed compliant with the

[1] A transmit spectral mask is the power contained in a specified frequency bandwidth at certain offsets relative to the total carrier power.

spectral requirements of the 802.11a specification. Their testbed was based on a single board Linux-based PC that hosted two interfaces and used the opensource MadWifi driver. The outdoors experiments in that work were the first to provide evidence of ACI. They report observing no board crosstalk or interference other than that caused by operating neighboring links on adjacent channels. They were the first to suggest increasing channel separation and antenna distance as well as using directional antennas in order to mitigate the effects of 802.11a ACI on the reduction of throughput. These were the first reports of 802.11a ACI, which, however, did not include any insight or attempts at some solid hypothesis as to why this ACI exists. However, ACI effects were clearly demonstrated, leaving no doubts about the existence of ACI in 802.11a.

In [1] the authors introduced a simple model to theoretically quantify ACI caused by overlaps in neighboring channels. Their key idea was focused on taking an integral over the whole overlapping region of the interfering channels spectral masks. They applied it to the spectral masks of 802.11b/g which have had known overlap issues due to poor channelization design, and also that of 802.16. They claim that the use of partially overlapped channels is not harmful, provided that higher layers take it into consideration and adapt accordingly. Furthermore they show that a careful use of some partially overlapped channels can often lead to significant improvements in spectrum utilization and application performance, with respect to the interfering nodes' distances.

In [4, 5] we introduced minor modifications to the limits of the integral used for the ACI quantification model introduced by [1] and were the first to apply it to the 802.11a spectral mask; we produced results on a testbed where the wireless channel was emulated using attenuators, and on a testbed with real outdoor mid-range wireless links using directional antennas. Those two works verified:

- Our hypothesis that ACI observed in 802.11a is caused by the overlap of the channel sidelobes allowed by the IEEE specifications
- That ACI can be caused by channels that are not only directly adjacent
- That ACI can be harmful if not taken into account during system and resource planning

The testbeds in all the above papers used Atheros-based wireless interfaces and the opensource MadWifi driver. This choice was made primarily because MadWifi was at the time the de facto reference driver for the vast majority of testbeds in the literature. Since then the MadWifi driver has been rendered obsolete, declared legacy, and is no longer supported by the Linux kernel.

In this work we provide new evidence that 802.11a ACI can be quantified and its effects predicted. In particular, we first demonstrate the existence of 802.11a ACI on a testbed with Atheros-based interfaces driven by the newly developed ath5k open source driver. Second, we quantify the ACI effect in terms of goodput, completely isolating the medium access control (MAC) and physical (PHY) layer mechanisms that are susceptible to its effect, using a wireless link emulation testbed.

System Model/ACI Quantification

The SINR criterion for data reception (Eq. 1) requires that the signal of interest power arriving at a receiver, over the sum of the interference and the thermal noise powers must be above a threshold which is defined with respect to the transmission parameters (modulation scheme) and the quality of service requirements (data rate of transmission and reception bit error rate [BER]). In Eq. 1 we assume k interfering transmitters operating on the same channel as the signal of interest transmitter, with powers P_i and P_{tx}, respectively.

$$\frac{P_{tx} \cdot PathLoss_{(tx,rx)}}{N_{rx} + \sum_{i=1}^{k} P_i \cdot PathLoss_{(i,rx)}} \geq \theta_{SINR} \tag{1}$$

Typically, the SINR criterion is applied, as in Eq. 1, in single-channel systems, where the interfering transmissions are assumed to occupy the entire bandwidth of the used channel and are considered noise. In a channelization scheme where more than one channels are used with some partial overlap on their bandwidth [1], an ACI factor $X_{i,rx}$ is introduced for each of the interferers, which can be used in the SINR calculations. This factor depends on the spectral properties of the channels and the transmitted signals, and the separation between the channels of an interferer i and the receiver rx. Specifically, the affecting properties are *the interchannel spectral distance*, *channel bandwidth*, *spectral mask*, and *receiver filter*. This factor takes values in [0, 1], with 0 indicating no overlap (i.e., complete orthogonality) and 1 indicating that the interferer is using the same channel as the receiver. For our work we calculate this interference factor by normalizing the spectral mask $S(f)$ within a frequency width w that should be at least equal to the nominal channel width, and then filter this normalized $S'(f)$ over the frequencies that will be within the bandpass filter of the receiver. Ideally, for the case of 802.11a, the spectral mask should be a flat bandpass 20 MHz filter, but for the sake of being more realistic we assume that the interfaces employed use a single imperfect, wider than nominal, bandpass filter both for transmission and reception. In the general case we could use Eq. 2 to obtain the *factor* $X_{i,rx}$ for an interferer i and a receiver rx, as a function of $R'(f)$, the normalized receiver filter transfer function in $[-w/2, w/2]$;

$$x_{i,rx} = \int_{\frac{-w}{2}}^{\frac{w}{2}} R'(f) S'_i(f - f_{\text{int}}) df, \tag{2}$$

where we have denoted f_{int} the frequency offset at which the interfering channel is centered (Fig. 1).

Due to the poor channelization of 802.11b/g that left only three of the available channels to be non-overlapping, the channelization scheme of 802.11a was over-advertised to offer 19 non-overlapping channels in the ETSI regulatory domain and 20 in the FCC domain.

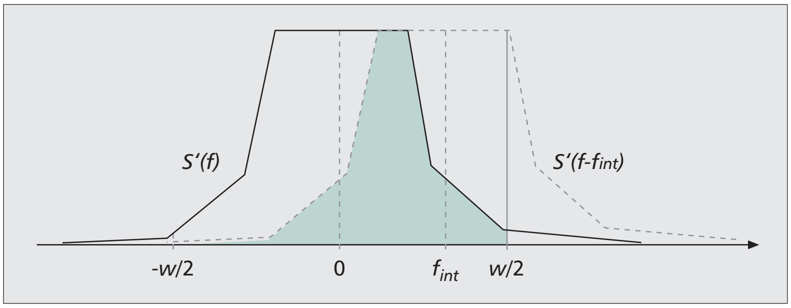

Figure 1. *Graphical representation of the calculation of Eq. 2.*

Receiver bandwidth	Immediately adjacent channel power leakage $X_{i,(i\pm1)}$	Next adjacent channel power leakage $X_{i,(i\pm2)}$
20 MHz	–22.04	–39.67
∞	–19.05	–36.67

Table 1. *Theoretically calculated* $X_{i,rx}$ *in dB.*

Finally, in a system where all radio interfaces adhere to the same protocol, it is reasonable to assume that all nodes have the same $S(f)$; and furthermore, that this output filter matches the receiver filter, and so: $S(\cdot) = R(\cdot)$. Under these two assumptions, Eq. 2 becomes

$$x_{i,rx} = \int_{\frac{-w}{2}}^{\frac{w}{2}} S'(f)S'(f - f_{\text{int}})df, \quad (3)$$

where we have denoted f_{int} the frequency offset at which the interfering channel is centered (Fig. 1).

Using this model and the spectral mask for 802.11a mandated by the standard in [2], we calculated the maximum compliant power leakage between two neighboring 802.11a channels. Table 1 shows the results of our calculations of the ACI $X_{i,rx}$ factor expressed in dB (essentially the attenuation of the transmitted power due to the frequency offset) that may be used directly in any link budget calculation.

Table 1 indicates that the interference factor X is sufficient for a single transmitter to inject ACI power at a receiver which will be well above the thermal noise in an 802.11a system under conditions enabled by proximity or power allocation, even if the interfering transmitter were using the next adjacent channel to that of the receiver. For example, assuming the typical thermal noise of –101 dBm and a 20 MHz 802.11a channel centered at 5600 MHz (channel 120) and zero antenna gains, an interferer on an adjacent channel (say channel 124 at 5620 MHz) transmitting at only 1 mW (0 dBm) within approximately 40 m of the receiver would be received above noise, reducing the perceived SINR by at least 3 dB within that range.

Therefore, because of the channel design in IEEE 802.11a, ACI will be observed and, if not properly considered, will cause degradation of a system's performance. We must note, though, that our calculations in Table 1 use the spectral mask mandated by the standard, which is an envelope for the actual implementations as vendors compete to achieve better specifications for their cards.

In order to experimentally verify our calculations we developed a testbed with off-the-shelf equipment. As in our previous work, we chose to emulate the wireless medium rather than using the air in order to remove its non-deterministic characteristics, avoid unknown interference, and eliminate the inherent wireless medium uncertainty from our investigation. This led us to a laboratory testbed where nodes' antenna connectors were interconnected using coaxial cables, attenuators, signal splitters, and combiners. We separated the MAC and PHY mechanisms that affect the efficiency of the protocol in the presence of ACI in order to obtain bounds for the worse cases.

The Communication Mechanisms Affected by ACI in 802.11

Data Reception Mechanism Errors

Assuming that the interference caused by 802.11a stations can be modeled as white Gaussian noise, we can determine whether the SINR requirements for the 802.11a transmission rates, given in the specifications for 10 percent packet error rate, can be met under the presence of ACI. Since each interfering node produces some ACI at the receiver, interesting interface topologies can be observed, arising by poor system design, where the total ACI will bring the SINR at the receiver below the threshold.

Multiradio Nodes — In a multiradio node, assignment of neighboring channels on interfaces that have their antennas close together has been shown to cause reduced performance [3]. In such a scenario the interference arriving at a receiver can be sufficiently high to be harmful due to proximity, which causes low interference path losses.

Single-Radio Nodes — In dense topologies where channel allocation may inevitably provide nearby links of adjacent channels, if the path losses to some receivers are high, or the number of concurrent interfering transmissions is large, their aggregate power may be high enough to bring the SINR below threshold.

Clear Channel Assessment False Negatives

IEEE 802.11 employs a distributed coordination function (DCF), which essentially is a carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol with binary exponential backoff. The DCF defines a basic access mechanism and an optional request-to-send/clear-to-send (RTS/CTS) mechanism. Let us consider just the basic access mechanism. In the DCF a station has to sense the channel as clear (i.e., idle) for at least a duration of *DIFS* + *CWmin* (both defined in [6]) in order to gain access to it. The 802.11a standard requires that a clear channel assessment (CCA) mechanism be provided by the PHY layer. The CCA mechanism that will provide this information is to proclaim a channel as busy when it decodes a PHY layer preamble at a power at least equal to that of the basic rate of the 6 Mb/s sensitivity,[2] or detects any signal with power 20 dB above the basic transmission rate 6 Mb/s sensitivity.

Interference can cause the CCA to misreport in the case of nearby located interfaces. A channel may be sensed as busy due to high received power from a neighboring channel that is interfering. This can occur when two nearby 802.11a transmitters contend over different channels, such as in a poorly designed multiradio node; for example, in a multiradio mesh node that has two or more interfaces using nearby channels, with omni- or directional antennas, and with insufficient spatial separation, or EM shielding between them.

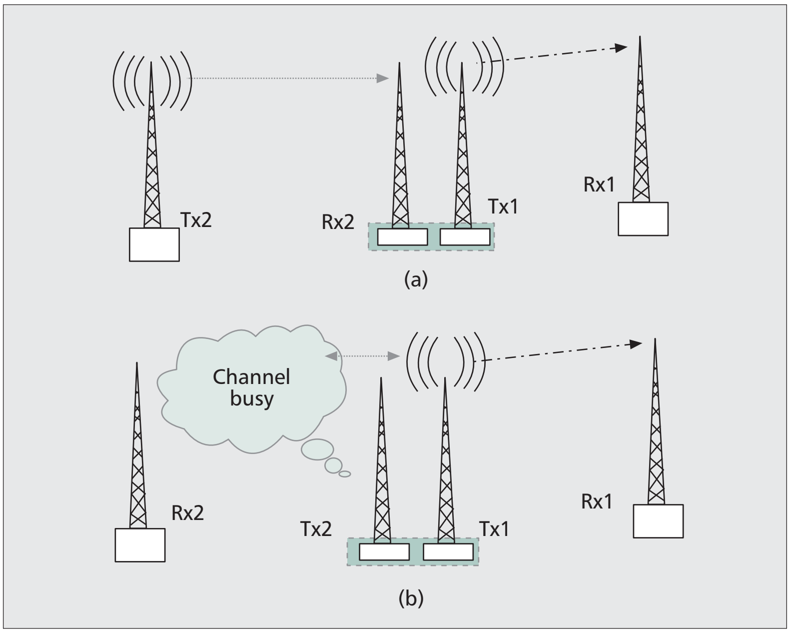

Figure 2. *The SINR effect on packet reception: a) Rx2 will not be able to correctly decode the data transmitted by Tx2 due to high interference from nearby channel transmission of Tx1; b) Tx2 may falsely report the channel as busy if channel Tx2 → Rx2 is adjacent to channel Tx1 → Rx1.*

EXPERIMENTAL VERIFICATION

TESTBED DESCRIPTION

The testbed of our experiments consisted of four nodes interconnected using cables and attenuators, eliminating the unpredictable wireless medium and thus fully controlling the transmission and reception paths and losses.

Each node is an EPIA SP13000 mini-ITX motherboard with a 1.3 GHz C3 CPU and 512 Mbytes RAM, running Gentoo Linux with the wireless testing tree kernel v.2.6.31-rc8-wl. With a RouterBoard miniPCI to PCI adapter, an Atheros AR5213A chipset miniPCI wireless interface card (*CM9-GP*) was used on each node, running on the ath5k 802.11a/b/g driver and hostapd v0.6.8. The ath5k driver was modified to independently use the two antenna connectors of the wireless card, one only for transmission and the other only for reception. This was the primary key enabler for the design of the experiments conducted.

We also used the AirMagnet Laptop Analyzer v6.1 software to monitor the wireless traffic and a Rohde & Schwarz FSH6 spectrum analyzer for channel power and bandwidth verification. The interconnectivity of the nodes was routed through coaxial cables, four-way HyperLink Tech splitters/combiners, Agilent's fixed attenuators (of 3, 6, 10, 20, and 50 dB), and programmable attenuators by Aeroflex/Weinschel with 0 to 55.75 dB attenuation range and steps of 0.25 dB. For the traffic generation and throughput measurements, we used the iperf v2.0.4 with pthreads enabled.

Before any measurement a bootstrap procedure was followed where the wireless interface was completely reset before applying the new settings, as a precaution catering to the unstable nature of the ath5k driver, as our experience has shown. We generated UDP traffic both in the interfering link and the link under test, to avoid the flow control mechanism of TCP and thus get results for the maximum goodput at the receiver.

EXPERIMENTS' SETUP

We set up just two links to realize the scenarios of Fig. 2. One is the test link (link, Fig. 3a) and the second is the interference link (interferer, Fig. 3a) to be tuned at a channel neighboring the one used first. With these two links we were able to generate the topologies of Fig. 2 and conducted two experiments. To avoid confusion, for both the link and interferer we use the terms source and destination for the nodes that produce and consume the iperf traffic, respectively. Note that the interferer was made completely unaware of the link by proper power assignment at the link's sender transmitter, and the losses and isolation along the paths leading to both the receivers in the interferer.

First we tested the ACI effect on the data reception mechanism. To do this, we injected the traffic from the interferer's sender to the receiving connector of the link destination. Using the values of Table 1, we calculated the transmission power required for the interference and the attenuator values in order to bring the SINR at the receiver below threshold.

In the second experiment set the effect of ACI on the CCA mechanism was examined. For this the testbed interconnection was slightly altered so that the interferer's sender was coupled with the receiver of the link's sender. The values for the attenuators again were calculated using Table 1 and taking in mind the CCA requirements.

HARDWARE, SOFTWARE, AND 802.11 ISSUES

Transmission Power Instability — A major aspect of the interference mechanism is the initial transmission power, which together with the path losses determine the received interference power. Unfortunately, early experiments showed that the power control in the ath5k driver is not yet stable enough; for given power settings the actual output power depended on the data rate of the transmitted data, which appeared to be arbitrary and not due to an expected power cutoff at higher rates. To deal with this instability,

[2] *Sensitivity is the minimum input power level at which decoding can be achieved at a desired BER in a given rate.*

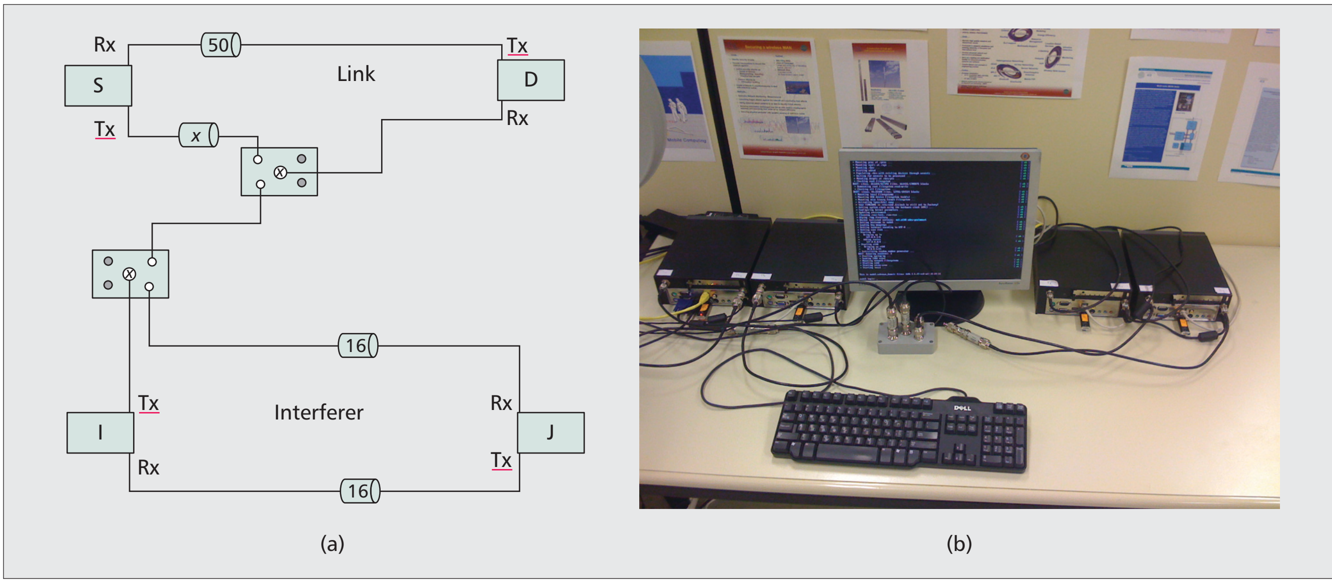

Figure 3. *a) The reception mechanism testbed layout schematic representation; b) the actual testbed of the experiments.*

at each data rate setting we measured the received power at some fixed point of our testbed during a calibration run, and based on the measured value we compensated accordingly by adjusting the attenuators.

In order to verify the theoretical assumptions presented earlier we coupled the measured SINR with the achievable throughput. In each data rate the expected throughput is relative to the SINR as for each constellation and coding rate the BER is directly linked to the signal-to-noise ratio (SNR) [7]. With the use of the programmable attenuator we were able to control the signal attenuation per dB; therefore, we obtained measurements that cover in detail a wide SNR space for each data rate.

Antenna Isolation Instability — Another major problem for designing and conducting the experiments was the separation of transmission and reception to the two antenna connectors on the wireless card. Unfortunately, disabling the antenna diversity option in the ath5k driver was not enough. The result was to have some sparse transmissions from the antenna connector designated for reception, reducing the accuracy of measurements. The problem was solved by making the appropriate corrections in the source code for the antenna connector handling in the ath5k driver.

Another interesting observation was that the ath5k/Atheros chipset combination had a periodical 3 s timeout during transmission. It was easily observed as a gap in the channel utilization graph during heavy traffic generation. This behavior could be attributed to the periodical recalibration of the radio frequency (RF) front-end the wireless cards perform. The result was a lack of interference during that period, giving a chance for unhindered communication in the link.

The Role of Channel Utilization — One key aspect of the interference generated by 802.11 devices is that it is not constant in time. It follows the timings of the 802.11 DCF, and can be considered noise that is there only during the time in which the interfering transmitter is active. Therefore, its effect will depend on the utilization of the interfering link. As seen in [8] the utilization of the wireless medium is inversely proportional to the data rate being used for a given achievable throughput. Quite an interesting observation is that even at the maximum achievable throughput, the utilization of the 54 Mb/s data rate is far lower than that of the 6 Mb/s rate. Therefore, one can expect that a 6 Mb/s interfering sender running at full throughput will be more harmful than a full throughput 54 Mb/s interferer.

With the interface connectivity explained earlier, we managed to produce an 802.11a jammer that does not sense the channel prior to transmitting, and therefore can transmit as frequently as a single user DCF allows, thus maximizing the utilization of the medium for its respective data rate.

Experimental Results

Packet Capture — The rate in the link under investigation was always fixed, having disabled the automatic rate selection mechanism. For each rate we increase the attenuation level at the programmable attenuator X (Fig. 3a) by one dB per measurement run. Essentially we decrease the SINR by one dB in each step and record the average throughput for a 3 min measurement run period. For each data rate we have a signal strength measurement for an attenuation value in order to have the differences in transmission powers between them. The differences in the transmission power of each rate are used to compensate the attenuation levels so that the results of the throughput are directly comparable. The results are presented in Fig. 4. It is obvious that the throughput curves closely follow the expected SINR — throughput degradation (e.g., as computed in [9]).

Interferer's Rate Effect — As already stated in the previous section, all the experiments were conducted with fixed rate and given utilization at the interferer. In this experiment we investigated whether the data rate of the interferer has any impact on the interference experienced by the receiver. In order to have comparable results for each data rate, we adjust the packet size to keep the utilization fixed. The results revealed that the data rate of the interferer has a strong impact, with increasing intensity at higher data rates. The reasons may be the constellation, which becomes denser at higher rates, and the transmission-idle time distribution. Since the ath5k driver always keeps the basic rate at 6 Mb/s to verify the above assumption, we also used a Cisco 1240 AP where different basic rates (6, 12, and 24 Mb/s) can be defined. With the Cisco AP we saw similar behavior, but with an even greater degradation in throughput. Although all the parameters were the same and it was expected that the devices should behave the same, we noticed that different devices do have some minor differences that result in different ACI. The differences can be attributed to protocol timing parameters as the Cisco AP consistently achieves higher throughput than the Atheros/ath5k in an interference-free environment.

In order to further investigate the transmitting-idling time distribution theory we used a series of packet sizes (1–1472 bytes) for the throughput measurement. We took a baseline measurement with absence of ACI and then produced ACI, keeping the same utilization with three different data rates (6, 24, 54 Mb/s). In 6 Mb/s we had a throughput degradation of 55–58 percent of the baseline, in 24 Mb/s 63–67 percent, and in 54 Mb/s about 80–91 percent with the greater degradation in larger packet sizes. This result verifies that the mechanism behind the rate effect of the ACI is the distribution of transmission and idle times, as the long-term medium utilization may be constant but the interleaved transmitting-idle periods are denser in higher data rates.

CCA — In this experiment we have set channel 60 for the test link and performed a baseline measurement of the achieved throughput using a 1000-byte UDP payload, without any interference and for all possible data rates (Table 2, column 1). The values of the attenuators were properly calculated so that an interferer with output power 0 dBm tuned to the adjacent channel would trigger false positives in the CCA mechanism of the test link sender. A second series (Table 2, column 2) was recorded with the interferer at the same channel as the test link where the CCA mechanism is expected to be triggered — this marks the results of a collocated and non-contending transmitter at the same channel as the link. Tuning the interferer at channel 56 resulted in a throughput loss ranging from 55 percent at 6 Mb/s to 85 percent at 54 Mb/s, which of course is due to the busy medium state that the transmitter is frequently sensing. As is obvious from Table 2, for the same transmission power level two channels away (channel 52), the CCA mechanism is not affected. In Table 1 we observe that the difference in power leakage between adjacent and next adjacent channels is 18 dB. With that in mind, we raised

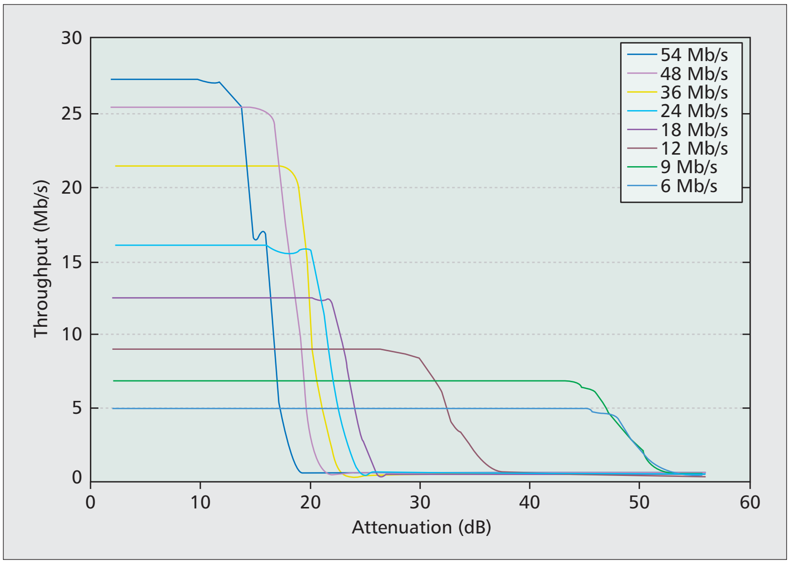

Figure 4. *Results of the packet capture experiment.*

Link at channel 60		Interferer at channel			
Tx rate (Mb/s)	**Baseline**	**60**	**56**	**52**	**52 (+18 dB)**
6	4.86	2.21	2.54	4.94	2.23
9	6.92	3.03	3.10	7.91	2.32
12	8.92	3.12	2.67	9.01	2.12
18	11.81	3.15	2.71	11.72	2.29
24	14.30	3.20	2.78	14.10	2.46
36	18.11	3.40	2.81	18.21	2.65
48	21.13	3.00	2.82	21.19	2.33
54	23.11	3.26	2.95	22.10	2.71

Table 2. *ACI effect on the throughput, in Mb/s, due to CCA false positives.*

the transmission power by 18 dB, and observed that the CCA mechanism was again triggered, verifying once more our model of Fig. 1. The similar results of all the columns where the CCA was triggered indicate the binary nature of the mechanism: if the received power exceeds the threshold, regardless of the channel distance, the medium is sensed as busy.

CONCLUSIONS

Despite the general belief that 802.11a is free of ACI, due to the use of non-overlapping channels, we have shown that the need for careful channel selection is also present in the 5 GHz band. Through the use of the emulated wireless medium, we have isolated the affected 802.11 mechanisms and quantified the throughput degradation due to ACI. The two main mechanisms that are affected are data reception and clear channel assessment. In the first case the SNR is degraded, making reception impossible, *The large number of channels available in 802.11a, taking into consideration the facts identified and justified in this article, provide the opportunity and motivation respectively for meticulous channel selection in order to achieve high throughput.*

and in the second case the transmitter stalls its data as it incorrectly senses the medium busy. Nevertheless, the large number of channels available in 802.11a, taking into consideration the facts identified and justified in this article, provide the opportunity and motivation for meticulous channel selection in order to achieve high throughput.

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ADDITIONAL READING

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BIOGRAPHIES

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