Reinvestigating Channel Orthogonality - Adjacent Channel Interference in IEEE 802.11n Networks

Anatolij Zubow and Robert Sombrutzki
Humboldt University
Rudower Chaussee 25, Berlin, Germany
Email: {zubow,sombrutz}@informatik.hu-berlin.de

***Abstract*—In this paper we analyze the adverse effects of Adjacent Channel Interference (ACI) on 802.11 with a focus on new 802.11n standard. ACI is causing problems that are related to the carrier sensing mechanism in 802.11. On the one hand, the carrier sensing is sometimes too restrictive thus preventing concurrent transmissions which leads to a variant of the exposed terminal problem. On the other hand, the carrier sensing is sometimes too optimistic thus causing packet collisions which is a form of the hidden node problem. Both problems are especially severe in multi-radio systems, where the radios are very closely spaced. Such problems already investigated in 802.11a/b/g still remain with 802.11n. Our results show that the number of available orthogonal channels in IEEE 802.11n depends on the spatial spacing between the radios, channel width (HT20 vs. HT40), RF band (2.4 vs. 5 GHz) and traffic pattern. In a multi-radio system the situation is worst, e.g. in the 2.4 GHz we were not able to find more than 1 orthogonal channel. The adverse effect of ACI can be reduced in two ways. First, by increasing the spatial separation between the radios; a spacing of less than 1 meter already improves the situation significantly, e.g. 40 cm are sufficient to get 2-3 orthogonal 20 MHz channels in the 2.4 GHz band with reduced transmission power. Furthermore, a distance of 90 cm is also sufficient so that a 40 and a 20 MHz channel can be used simultaneously without any interference. However, in a multi-radio system the spatial spacing between the radios cannot be increased due to space limitations. The only option to overcome ACI related problems is to reduce the transmit power making power control essential. Finally, our analysis revealed that 802.11 is an inappropriate protocol for multi-channel MAC/routing protocols based on multi-radio systems where an explicit MAC layer link-scheduling is more promising.**

***Index Terms*—Wireless Networks, IEEE 802.11n, Multi Channel, Multi Radio, Adjacent Channel Interference, Orthogonal Channels, Measurements**

I. Introduction

Wireless networks based on standards like IEEE 802.11 are an important research topic in industry and academia. To increase the network capacity lots of work was done on multi-channel MAC and routing protocols that simultaneously use the multiple channels available in IEEE 802.11 [1]. The majority of multi-channel protocol designers assume the existence of several non-overlapping and therefore non-interfering (orthogonal) channels, e.g. 3 for 802.11b/g and 12 for 802.11a, when evaluating their protocols. While implementing real-world prototypes of their multi-channel protocols, some authors realized that Adjacent Channel Interference (ACI) between supposable non-overlapping channels causes serious problems when used with 802.11. The impact from ACI was much higher in multi-radio systems where network devices are equipped with multiple 802.11 radios, since the spacing between antennas of different radios is small due to space constraints.

In contrast to strictly using only non-overlapping channels it is also possible to further increase the available network capacity by simultaneously using overlapping channels. However, this requires a careful planning of channel assignment taking into account aspects like spatial spacing between radios, used PHY modulation and RF band as well as traffic pattern [2]. Otherwise problems like the hidden and exposed terminal problem would significantly increase due to ACI and waste a large amount of the available radio resources (ref. to III-C). Thus there is a tradeoff between spectral efficiency and impact from ACI related problems as depicted in Fig. 1.

The majority of multi-channel protocol research is based on the outdated 802.11a/b/g standard. However, the updated 802.11n standard [3] offers lots of improvements like the use of wider channels (channel bonding) and the use of less guard carriers which have an effect on channel orthogonality. Moreover, the signal filtering was improved, i.e. less energy is bleeding over to adjacent channels. Finally, earlier studies have shown that some hardware and software solutions based on the legacy 802.11a/b/g standard showed incorrect behavior [2]. Therefore, it is necessary to examine the influence of ACI in 802.11n again using state-of-the-art hardware and software.

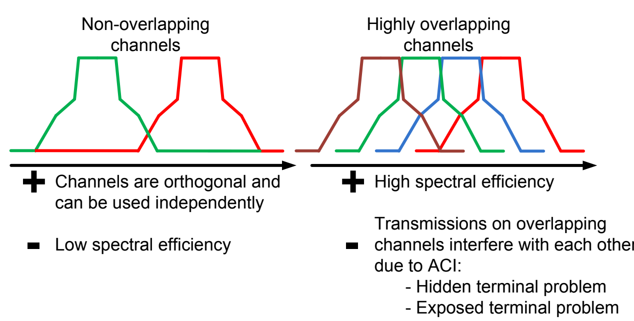

Fig. 1. Trade-off, which occurs with simultaneous use of multiple channels when using a Carrier Sense Multiple Access (CSMA) protocol (e.g. 802.11).

The main contributions of this paper are as follows. First, we describe the adverse effects of Adjacent Channel Interference (ACI) on 802.11 like the increased probability for hidden and exposed terminal problems. Second, we give a brief overview of the radio spectrum usage in 802.11 with the focus on 802.11n. Third, we present experimental results showing the impact of ACI on 802.11n and compare them with results for 802.11b/g. In contrast to other studies we take a holistic view on the impact of ACI. Thus we are able to separate the impact of ACI on the individual components of 802.11 - Clear Channel Assessment (CCA) at the transmitter and error correction at the receiver. Fourth, we discuss the impact of our results on current research fields. Here we identify promising research areas as well as research directions where we think that they have only little prospects. We conclude our paper by summarizing the results.

II. Related Work

The impact of ACI on 802.11b/g/a was extensively studied [2], [4]–[11]. The studies can be classified in whether multi-radio systems, i.e. a network node is equipped with multiple 802.11 radios, or single-radio systems were analyzed.

For multi-radio systems, Draves et al. [5] could not find any non-interfering channels within 802.11b/g and 802.11a. The disillusioning result was that they had to operate one radio in the 2.4 GHz and the other in the 5 GHz band. Of the expected 15 non-interfering frequency channels only two remained. The first systematical measurement was conducted by Robinson et al. [6]. They observed that merely plugging an additional wireless card into a PC workstation and operating it in a passive monitor mode can reduce the throughput. They accounted this to board crosstalk and radiation leakage of the passive cards.

Regarding single-radio systems, Adya et al. [4] found out that separating two radios by at least 30 cm 3 non-interfering channels became available for 802.11b/g. Other researchers proposed a spatial spacing between radios of 1 m to get at least 2 non-interfering channels within 802.11b/g [7], [9], [10]. Finally, Cheng et al. presented also limited results for 802.11a [8], [12].

In our previous study we evaluated 802.11b/g/a for both multi-radio as well as single-radio systems [2]. The results can be summarized as follows: The number of available non-interfering channels depends on the spatial spacing between radios, PHY modulation, RF band (2.4 vs. 5 GHz), traffic pattern and whether single- or multi-radio systems are used. A general statement about channel orthogonality in 802.11 cannot be made. ACI was identified as main problem. For nearby transceivers (multi-radio systems) at most 2 noninterfering channels, one within 2.4 GHz and the other within the 5 GHz band was identified. Moreover, we observed asymmetric packet flows depending on the considered traffic pattern. Furthermore, we also observed hardware and software related problems. The combination of Atheros chip (AR5414) together with Madwifi driver showed an incorrect behavior at channel 11 and 12.

The most recent work on ACI together with the upcoming 802.11n standard can be found in [13]. The authors analyzed the impact of channel bonding in 802.11n. However, the used experimental setup allowed them to analyze the impact of ACI on Clear Channel Assessment (CCA) only. The main observation was that using 40 MHz channels in an unplanned fashion can lead to serious throughput degradation thus a careful modeling of interference is required.

Other related observations were that ACI is highly hardware dependent [4] and that channel crosstalk exists when using 802.11b; i.e. an 802.11b receiver was able to receive packets on neighboring channel from a nearby transmitter [11].

III. Background

The objective of this section is threefold. At first we describe the adverse effects of Adjacent Channel Interference (ACI) on 802.11 namely a variant of the hidden and the exposed terminal problem. Thereafter, we give a brief overview on how carrier sensing and signal detection of a typical IEEE 802.11 radio works. This is necessary to understand the impact from ACI on CCA. Finally, the radio spectrum usage of the different 802.11 PHY modes is presented. The focus here is to address the particularities of 802.11n.

A. Hidden Terminal Problem

The Hidden Terminal Problem (HTP) is a well analyzed problem [14]. It happens when transmissions from two nodes, that cannot hear each other, collide at the receiver for one of the nodes. Various solutions to solve this problem have been proposed to address the problem [15]. The 802.11 standard recommends the use of RTS/CTS exchange to avoid hidden terminal problems.

B. Exposed Terminal Problem

The Exposed Terminal Problem (ETP) occurs when a node is prevented from sending due to the presence of another transmitter nearby. This occurs because the carrier sense mechanism (CCA) used in 802.11 is conservative, and prevents a node from transmitting when another node is transmitting, for the fear of causing a collision. Several solutions to this problem have been proposed as well [16]. Most proposals require modifications of the carrier sensing mechanism.

C. Adjacent Channel Interference

Adjacent Channel Interference (ACI) is a form of interference that is caused by nearby transmitters on distinct frequency channels ”bleeding over” to another channel [17, p. 74].

When using 802.11 ACI has the following consequences: For the case of two nearby transmitters the overlapping ACI of one transmitter causes a spurious carrier sensing at the other thus preventing two concurrent transmissions (Fig. 2(A)). Remember that 802.11 is a CSMA protocol which follows the listen-before-talk paradigm. That means that a station is only allowed to transmit if the medium is idle. ACI may trigger the carrier sensing mechanisms to report that the medium is busy. In this case the station will misleadingly defer its transmission. However, at both receivers there is a sufficient high signal-to-interference ratio so that it would be possible to successfully decode both signals. Note, the effect of ACI is smaller than that of co-channel interference because only a small amount of energy is ”bleeding over” to another channel. Thus ACI causes a variant of the Exposed Terminal Problem (ETP) which significantly reduces the spatial reuse in the network and thus wasting radio resources.

In addition to the ETP a variant of the Hidden Terminal Problem (HTP) can be caused by ACI. Here we distinguish between two cases. For the case of a receiver and a transmitter on adjacent channels in close proximity the weak incoming signal at the receiver gets corrupted by the ACI from the strong outgoing signal of the nearby transmitter (Fig. 2(B1)). The reason for that is that the interfering sender (S_2) is unable to sense an ongoing transmission from S_1 to R_1 via CCA. In contrast to the above ETP problem here the CCA mechanism is not sensitive enough.

We also observed a problem for two receiving nodes in close vicinity (Fig. 2(B2)). Here ACI corrupts the weak signal at both receivers. In contrast to the above HTP problem here both transmissions are suffering. Again, ACI causes a variant of the HTP that like the one before cannot be tackled with RTS/CTS since the two links are on distinct channels and therefore the receiver is unable to decode the NAV value from the RTS/CTS packets. We will later show that even for two nodes in very close proximity it is not possible to receive a packet send on an adjacent channel (crosstalk)[1].

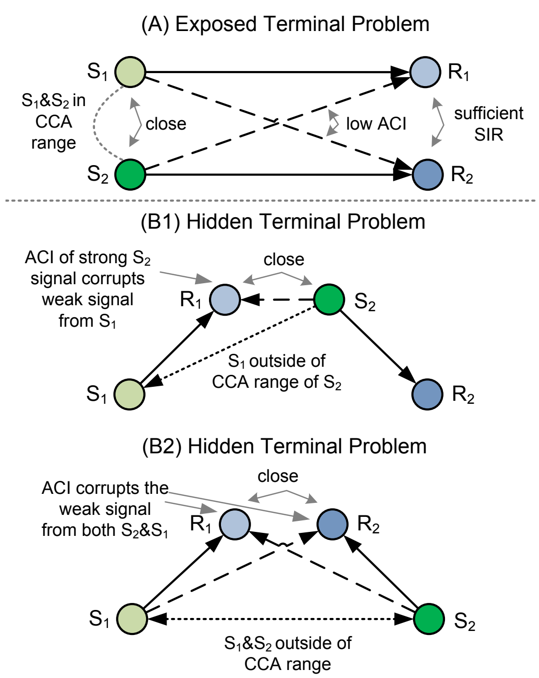

Fig. 2. Variants of the exposed terminal and hidden terminal problem caused by ACI when using overlapping channels in 802.11. Two packet flows were setup: S_1 to R_1 and S_2 to R_2.

[1]Crosstalk is partially working for 802.11b, whereas it is not working for the OFDM phycical layer (802.11a/g/n) at all.

D. Understanding Carrier Sensing

In the following we give a brief introduction on how carrier sensing and signal detection of a typical IEEE 802.11 radio works. This helps us to understand on how they are affected by ACI. In 802.11 each packet contains a preamble, which is used for signal (packet) detection by the receiving radio. An 802.11 radio must implement a signal detection mechanism and a carrier sensing mechanism to support CSMA. The carrier sensing mechanism is used to detect ongoing transmission, so that in a node can retain its transmission. Note that the 802.11 standard also specifies a Virtual Carrier Sensing (VCS) mechanism, which requires for the receiver to actually decode the packet to read the included Network Allocation Vector (NAV). However, for 802.11a/g/n it is only possible if the correct channel is used, i.e. channel crosstalk is not working except to some degree in 802.11b. So my means of VCS it is not possible to detect an ongoing 802.11a/g/n transmission on a neighboring channel. Therefore, modern radio chipsets implement a variety of signal processing features to support signal detection. Atheros radio chipsets use two joint signal detection algorithms [18]. The strong signal detection algorithm tries to detect incoming packets by monitoring sudden changes of the received signal power, whereas the weak signal detection performs a correlation-based detection algorithm that takes advantage of the structure of the preamble signal (ref. to [18]). Figure 3 shows a simplified representation of the three most important blocks associated with signal reception and carrier sensing [19]. The first two blocks address signal detection whereas the third block is an energy detection block parameterized by a threshold. We believe that these signal and energy detection blocks are making it possible to detect an ongoing 802.11 transmission on a neighboring channel.

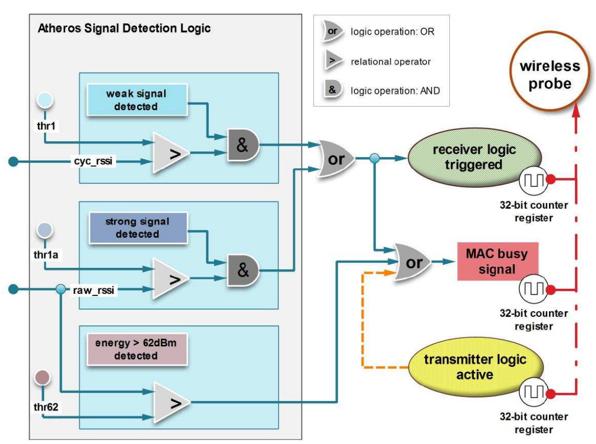

Fig. 3. Schematic representation of the three most important blocks associated with packet reception and carrier sensing (from [19]).

E. Radio Spectrum Usage

1) 802.11b/g/a: The DSSS PHY has at most 13[2] channels in the 2.4 GHz band with channel spacing of 5 MHz. Channel

[2]in Japan there is an additional channel 14.

1 is centered at 2.412 GHz, channel 2 at 2.417 GHz, and so on.Within a channel, most of the signal energy is spread across a 22 MHz band (Fig. 4). To prevent interference to adjacent channels, the first side lobe is filtered to 30 dB below the power at the channel center frequency. Additional lobes are filtered to 50 dB below the power at the channel center [20]. ACI influences the number of channels that can be used simultaneously. The IEEE 802.11b specifies that 25 MHz spacing is sufficient.

The multi-carrier (OFDM) PHY in the 5 GHz band offers 8 channels for indoor and 11 for outdoor use, each 20 MHz wide. In comparison to the 2.4 GHz band the channel spacing's are larger – 20 instead of 5 MHz [20]. The 802.11a transmission spectrum mask is described in the specification as: "The transmitted spectrum shall have a 0 dBr bandwidth not exceeding 18 MHz, -20 dBr at 11 MHz frequency offset, -28 dBr at 20 MHz frequency offset and -40 dBr at 30 MHz frequency offset and above." [21] (Fig. 4).

According to 802.11g the multi-carrier OFDM PHY is also available in the 2.4 GHz band. The transmit mask is the same as for 802.11a.

2) 802.11n: The most important modification in 802.11n having an impact on ACI is the use of wider channels (channel bonding). Channels having a bandwidth of 40 MHz, called HT40, can be used which effectively doubles throughput. Moreover to improve the spectral efficiency the number of OFDM data subcarriers was increased from 48 to 52 which reduces the number of guard (null) carriers and thus might increase ACI on neighboring channels.

The 802.11n transmission spectrum mask is described in the 802.11n specification as: "When transmitting in a 20 MHz channel, the transmitted spectrum shall have a 0 dBr bandwidth not exceeding 18 MHz, -20 dBr at 11 MHz frequency offset, -28 dBr at 20 MHz frequency offset, and the maximum of -45 dBr and -53 dBm/MHz at 30 MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 4 (left). When transmitting in a 40 MHz channel, the transmitted spectrum shall have a 0 dBr bandwidth not exceeding 38 MHz, -20 dBr at 21 MHz frequency offset, -28 dBr at 40 MHz offset, and the maximum of -45 dBr and -56 dBm/MHz at 60 MHz frequency offset and above." [3] The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 4 (right).

3) Discussion: By comparing the transmission spectrum masks of the different 802.11 PHY modes with each other we observe the following. The signal in 802.11b is best filtered. Starting at a frequency offset of 22 MHz, the signal is already attenuated by 50 dB. Thus the ACI impact should be the lowest. In 802.11n (20 Mhz) the filtering of the OFDM signal was improved compared to 802.11a/g - the signal at a frequency offset of 30 MHz and more must be attenuated by 45 instead of 40 dB. Therefore it is interesting to analyze if this has an impact on the number of orthogonal channels.

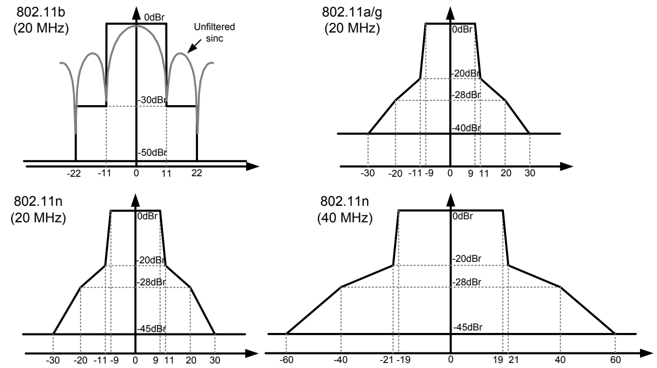

Fig. 4. Transmit spectral mask for 802.11b/g/a as well as 802.11n (20 MHz and 40 MHz channel).

IV. EVALUATION

The objective of this section is to evaluate the impact from ACI on the performance of 802.11 with a major focus on 802.11n. At first we present the used experimental methodology. Thereafter the results are presented and discussed.

A. Methodology

The experimental setup is given in Fig. 5. We considered the following three scenarios termed as: (i) TX-TX, (ii) RX-RX and (iii) TX-RX. In the TX-TX scenario both middle nodes (M_0 and M_1) transmit at the same time. Two packet flows were setup as follows: $M_0 \rightarrow L$ and $M_1 \rightarrow R$. To obtain strictly directive flows MAC layer broadcasts were used, i.e. no acknowledgment packets were sent out. For non-interfering channels one would expect that both radios in the middle can transmit in parallel. So the total throughput should equal the sum of the single packet flows. In the RX-RX scenario both nodes in the middle are the destinations of two flows originated in L and R respectively. Since two flows can be received simultaneously, one would again expect a significant throughput increase when using two non-interfering channels. Finally, in the TX-RX scenario the node L sends packets to M_0 while at the same time M_1 transmits to the right node. This scenario mimics a forwarding operation of a relay in a multi-hop mesh network.

Our objective in considering these three different scenarios is to analyze problems in 802.11 connected to ACI in a isolated way. With the help of the TX-TX scenario we intend to analyze the adverse effects from ETP, whereas the other two scenarios are used to show the impact from HTP.

To systematically analyze the impact from ACI we used a moving robot (Fig. 5, right). We automatically varied the distance between M_0 and M_1 (d_1) from 10 cm to 140 cm in 10 cm steps, of which a separation of 10 cm mimics a multi-radio device, i.e. a device equipped with two or more radios. Distances d_2 and d_3 were around 400 and 500 cm respectively. The link between nodes L and R is obstructed by a thin wall.

The goal was to mimic a link with medium SNR. All nodes were placed 80 cm above the ground and had clear line of sight to each other with the exception of the link between L and R. Moreover we evaluated different TX power level to differentiate the impact on weak and strong links respectively.

We used Netgears WNDR3700v2 (680 MHz Atheros MIPS CPU) equipped with two Wifi interfaces (Atheros AR9220 and AR9223 chipset)[3] and 8 internal metamaterial antennas from Rayspan[4]. On the software side we chose OpenWrt[5] with Linux kernel 2.6.32 as operating system and ath9k[6] as WiFi driver. The packet generation and capturing was done with the Click Modular Router[7] software version 2.0 and additional elements for 802.11n support (see [22]). All nodes were running in WiFi monitor mode. During the measurements only one radio was active. During transmission and reception we monitored that the CPU load remained within safe grounds and did not become the bottleneck. The measurements took place at night, so interference due to external wireless networks was negligible.

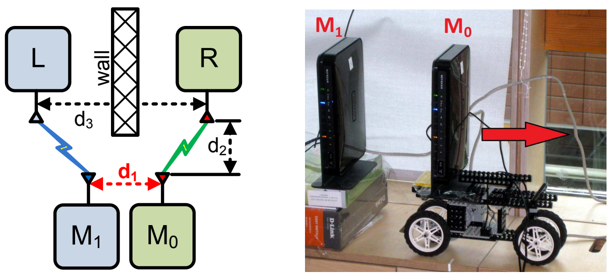

Fig. 5. Measurement setup consists of 3 fixed (M_1, L and R) and a single moving node (M_0).

Besides 802.11n bitrates[8] we considered the DSSS (802.11b) and the OFDM physical layers (802.11g/a) with a bitrate of 5.5 and 6 Mbps, respectively. Broadcast MAC frames with a size of 2300 Bytes (802.11a/b/g) and 3832 Bytes (802.11n) were sent out as fast as possible (backlogged queues). As mentioned since MAC layer acknowledgments were not used, we were able to obtain strictly directive flows. For all experiments the link between L and M_0 was fixed at channel 1 for 802.11b/g/n and 149 for 802.11a/n, respectively, while the channel for the link between M_1 and R was varied from 1-11 and 149-165 respectively (Fig. 5). Note, that in the 5 GHz band for the used US country code the largest working contiguous frequency range we found was 5 channels - channel 149-165. The channels ranging from 52 to 116 were not correctly working. Interestingly, these are exactly those that require dynamic frequency selection (DFS). If not otherwise stated for 40 MHz channels in 802.11n we used HT40+, i.e. the depicted channel is the center frequency of the lower 20 MHz band. E.g. for a HT40+ transmission on channel 1 the upper 20 MHz band is centered on channel 5. Note, that using HT40+ the channel 165 becomes unavailable. For each scenario and channel assignment the experiment lasted 30 s. Beforehand, the links were independently measured to ensure that the signal is strong enough and the Packet Error Rate zero for all links and the channel utilization[9] was low.

[3]More details on the used hardware can be found in [22]
[4]see http://www.commnexus.org/assets/011/9474.pdf
[5]OpenWrt Linux distribution for embedded devices: http://openwrt.org
[6]Linux-Wireless: http://http://linuxwireless.org
[7]The Click Modular Router: http://www.read.cs.ucla.edu/click/
[8]With bitrate we refer to a specific modulation and coding scheme (MCS) available in 802.11n.

Parameter	Value
Location	Indoors
Systems	Netgear WNDR3700v2
Scenarios	TX-TX (M_0 + M_1 transmitting), RX-RX (M_0 + M_1 receiving), RX-TX (M_0 receiving, M_1 transmitting)
Antenna separations	10-140 cm (10 cm steps)
Physical layer	802.11a/b/g/n
Transmission power	16 & 27 dBm (2.4 GHz) 12 & 17 dBm (5 GHz)
Bitrates	1 Mbps (.11b), 6 Mbps (.11g) , 6.5 Mbps (.11n, MCS=0, 20 MHz), 13 Mbps (.11n, MCS=0, 40 MHz)
Radio frequencies	2.4 GHz (ch. 1–11), 5 GHz (ch. 149–165)
Transmission mode	MAC Broadcast
WiFi frame size	3832, 2300 Bytes
RTS/CTS	Disabled
Flow duration	30 sec
WiFi country code	United States (US)

TABLE I
MEASUREMENTS PARAMETERS

The remaining parameters we used throughout our measurements are summarized in Table I.

B. Results

The results section is divided in two parts. At first we present results for the 2.4 GHz ISM band, afterwards results for the 5 GHz band are presented. For the analysis the most important statistics were: (i) sending rate at the transmitting nodes and (ii) receiving rate at the receiving nodes. Both statistics were computed on MAC layer as well as NIC based. For the later one the performance registers of the Atheros driver were read-out (ref. to [22]). The NIC-based results leading to the same conclusions were kept out due to space limitations.

1) 2.4 GHz Band: The results for the 2.4 GHz band are presented in this section. The plots presented in Fig. 6-8 are divided into two parts: left and right of the dashed line we present the results for the TX power of 27 dBm and 16 dBm respectively. Assuming a typical LOS pathloss model the distance of 50 cm at 27 dBm TX power is roughly equivalent to the distance of 10 cm at 16 dBm TX power. Note, that the full TX power of 27 dBm with a distance of 10 cm mimics a multi-radio system, i.e. two radios in one network node[10]. For our conclusions we assume that 11 channels are available in the 2.4 GHz band.

[9]As reported by Atheros performance registers (see [22]).
[10]We are aware of the fact that our setup does not consider any other sources of interference like board crosstalk.

a) TX-TX Scenario: In this section we evaluate channel orthogonality for two transmitting radios in close vicinity. We setup two flows: $M_0 \rightarrow L$ and $M_1 \rightarrow R$ (ref. Fig. 5). Figure 6 shows the send as well as the receive rate at M_1 and L respectively. Three different setups were evaluated: (i) both flows use 802.11n, (ii) one flow is a 802.11n 40 MHz channel (HT40+), the other 802.11g, (iii) one flow is 802.11b, the other is 802.11g.

In the TX-TX scenario the spatial spacing between both transmitters plays a crucial role. In a multi-radio system the spacing between the radios is small which makes it impossible to use more than 1 channel in the 2.4 GHz band. However, by reducing the TX power from 27 to 16 dBm 2 orthogonal channels become available even for a very close spatial spacing. When using a high TX power a spatial spacing of at least 20 cm is necessary so that 2 orthogonal channels become available. When using a 40 and a 20 MHz channel a spatial spacing of at least 30 cm or a reduced TX power of 16 dBm is required to get 2 orthogonal channels.

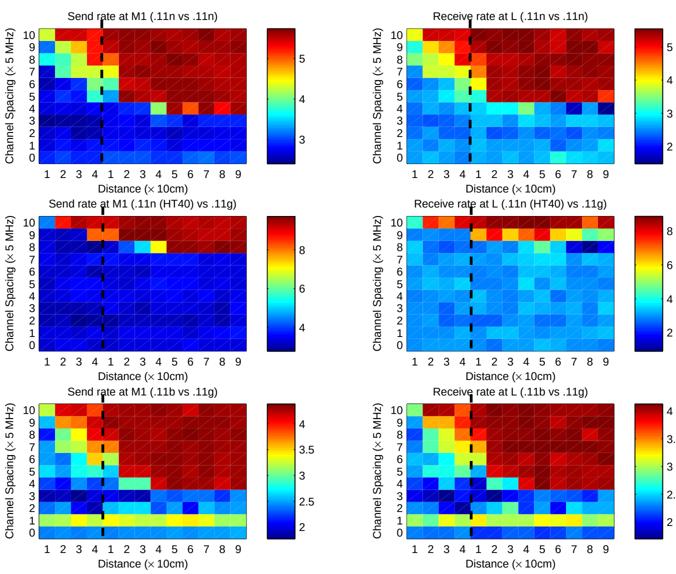

Fig. 6. TX-TX scenario, 2.4 GHz band. The send/receive rate is given in Mbit/s.

b) RX-RX Scenario: Fig. 7 shows the results for the RX-RX scenario. Here the spatial spacing between both receivers plays no role. For 802.11g as well as 802.11n a spacing of 5 channels is sufficient which results in 3 orthogonal channels. When using 802.11b together with 802.11g/n a channel spacing of only 4 is required[11]. This is mainly due to the better signal filtering in 802.11b. When using a 40 MHz (HT40+) together with a 20 MHz channel a channel spacing of 10 is required so that both streams will not interfere with each other resulting in 2 orthogonal channels.

c) TX-RX Scenario: Fig. 8 presents the results for the TX-RX scenario. Here the situation is much more complicated. To make our multi-channel relaying scheme possible, both the transmitter M_0 and the receiver M_1 need channel spacing so that they both can send/receive at the maximum rate. From our results we see that the sending node M_0 requires less spatial spacing to be able to send at a full rate. In a multi-radio system even with a reduced TX power it is impossible to use more than 1 channel in the 2.4 GHz band. Only by increasing the spatial spacing beyond 20 cm permits 2 orthogonal channels. By reducing the TX power to 16 dBm together with a spatial separation of at least 40 cm it is possible to use 3 orthogonal channels in 2.4 GHh band. When using a 40 and a 20 MHz channel a reduced power as well as a spatial separation of at least 90 cm is required to get 2 orthogonal channels.

[11]The same is true if only 802.11b is used.

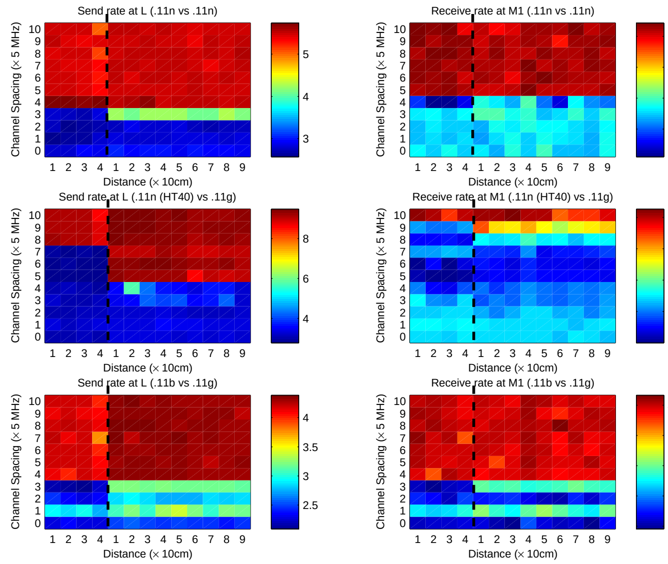

Fig. 7. RX-RX scenario, 2.4 GHz band. The send/receive rate is given in Mbit/s.

d) Summary: Table II summarizes the results for the 2.4 GHz band. The depicted channel spacing was estimated as follows: (i) in the TX-TX scenario it is the required channel spacing so that both transmitters M_0 and M_1 can send with the maximum rate. We do not take care whether the packets were also correctly received at both receivers L and R. What counts is the send rate at the transmitters measured at the MAC layer. (ii) in the TX-RX scenario we present the required channel spacing so that the receiver M_1 receives at full rate (flow: $L \rightarrow M_1$) while the transmitter M_0 is able to send at the maximum rate (flow: $M_0 \rightarrow R$). Note, that we ignore both the send and the receive rate at L and R respectively. In general the sending node requires less channel spacing to be able to send at full rate. Therefore, we examine both cases separately, i.e. TX-RX (TX) and TX-RX (RX) represent the required channel spacing so that the transmitter M_0 and the receiver M_1 can send/receive at maximum rate respectively. (iii) in the RX-RX scenario it is the required channel spacing so that both receivers M_0 and M_1 can receive with the maximum rate.

2) 5 GHz Band: The results for the 5 GHz band are summarized in Table III.

As with 2.4 GHz in the TX-TX scenario the spatial separa-

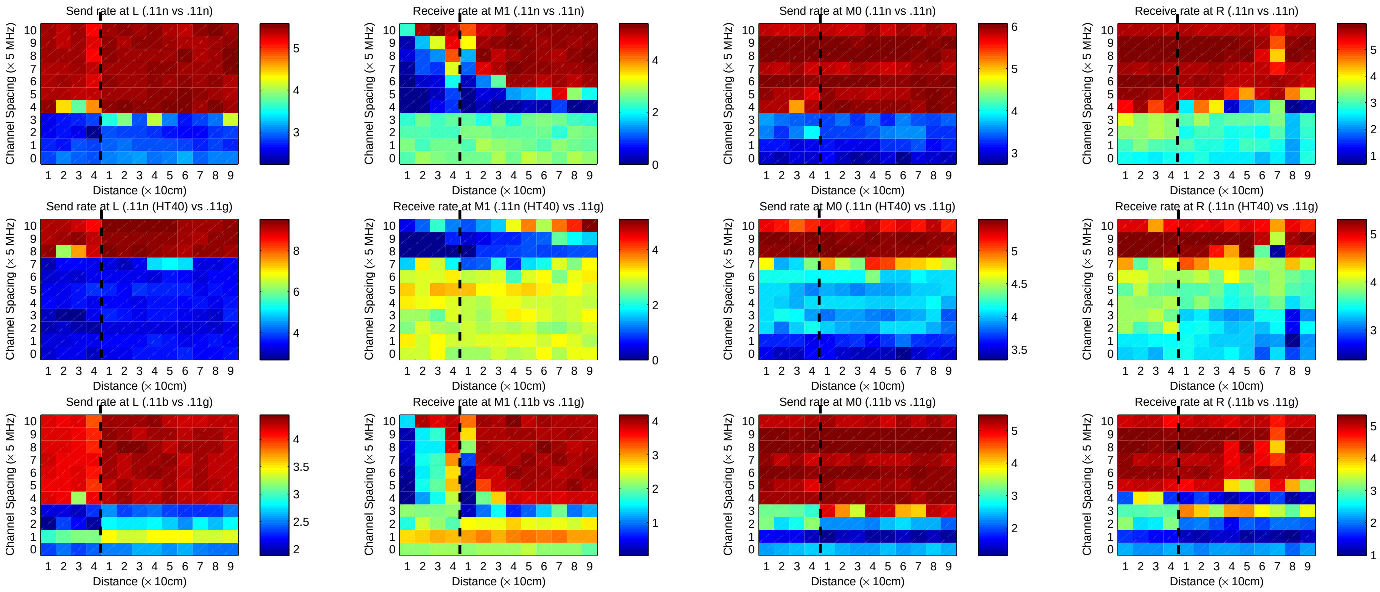

Fig. 8. TX-RX scenario, 2.4 GHz band. The send/receive rate is given in Mbit/s.

Scenario	802.11b vs. 802.11g		802.11g vs. 802.11g		802.11n: HT20 vs. HT20		802.11n (HT40) vs. 802.11g	
	16dbm	27dbm	16dbm	27dbm	16dbm	27dbm	16dbm	27dbm
TX-TX	10 - 20 cm : 9 20 - 40 cm : 5 40 cm - : 4	10 - 20 cm : n/a 20 - 40 cm : 10 40 cm - : 8	10 - 20 cm : 9 20 - 40 cm : 5 40 cm - : 4	10 - 20 cm : n/a 20 - 40 cm : 10 40 cm - : 8	10 - 20 cm : 9 20 - 50 cm : 5 50 cm - : 4	10 - 20 cm : n/a 20 - 40 cm : 10 40 cm - : 8	10 cm : 10 20 - 40 cm : 9 40 cm - : 8	- 30 cm : n/a 30 cm - : 10
TX-RX (RX)	10 cm : n/a 20 - 30 cm : 5 40 cm - : 4	10 cm : n/a 20 - 30 cm : 10 40 cm : 8	10 - 20 cm : n/a 20 - 40 cm : 7 40 cm - : 6	10 - 20 cm : n/a 20 - 40 cm : 10 40 cm : 9	10 -20 cm : n/a 20 -40 cm : 7 40 cm - : 6	10 - 20 cm : n/a 20 - 30 cm : 10 40 cm : 9	10 - 90 cm : n/a 90 cm : 10	n/a
TX-RX (TX)	4						8	
RX-RX	4 (802.11b) 5 (802.11g)		5				10 (802.11n) 9 (802.11g)	

TABLE II

IMPACT OF ACI FOR DIFFERENT SCENARIOS AND CONFIGURATIONS IN THE 2.4 GHz ISM BAND. SHOWN IS THE CHANNEL SPACING.

tion between both transmitters ($M_0 + M_1$) is very important. For the multi-radio system case we were not able to find 2 orthogonal channels, i.e. in a frequency chunk of 100 MHz it is not possible to use two channels independently. Again, increasing the spatial separation between the two transmitting nodes helps: when using two 20 MHz channels a spatial separation of 20 cm is required so that a channel spacing of 4 is sufficient. Furthermore the required channel spacing can be halved when the spatial separation is increased to 90 cm or beyond. Again reducing the TX power has a similar effect like increasing the spatial separation.

In the TX-RX scenario we again see that the reception at M_1 requires the most channel spacing. The relaying case is not possible with only 5 available channels. Even reducing the TX power does not help which is bad news for multi-radio systems. Only by increasing the spatial separation to 30 cm allows us to use two orthogonal 20 MHz channels. By further increasing the spatial separation to 70 cm we can use three 20 MHz channels simultaneously. A spatial separation of 80 cm is sufficient to simultaneously use two 40 MHz channels. Here we see the decisive advantage of wider channels; in a frequency chunk of 100 MHz it is possible to use two 40 MHz but only three 20 MHz channels independently.

In the RX-RX scenario the spatial spacing between both receivers plays no role. A channel spacing of 2 is sufficient when using two 20 MHz channels. In case of a 40 and a 20 MHz or two 40 MHz channels a spacing of 3 channels is required.

V. IMPLICATIONS

Our results have significant implications on what areas of research are promising and which have only small prospects. This will be discussed in the following.

A. Research Areas with little Prospects

In the following we present research areas which we believe they have little prospects.

a) Multi-channel Protocols on MAC/Routing Layer: This research is related to the availability of multiple orthogonal channels in 802.11 which can simultaneously be used to improve the network capacity. Lots of multi-channel protocols

Scenario	802.11n: HT20 vs. HT20		802.11n: HT20 vs. HT40		802.11n: HT40 vs. HT20		802.11n: HT40 vs. HT40	
	12dbm	17dbm	12dbm	17dbm	12dbm	17dbm	12dbm	17dbm
TX-TX	10 cm : 4 20 - 30 cm : 3 40 cm - : 2	10 cm : n/a 20 - 30 cm : 4 40 - 80 cm : 3 90 cm - : 2	10 - 20 cm : n/a 20 - 60 cm : 3 70 cm - : 2	10 - 50 cm : n/a 60 - 80 cm : 3 90 cm - : 2	10 - 20 cm : n/a 30 - 60 cm : 4 70 cm - : 3	10 - 60 cm : n/a 70 - 80 cm : 4 90 cm - : 3	10 - 60 cm : n/a 70 - 120 cm : 3 130 cm - : 2	10 - 120 cm : n/a 130 cm - : 3
TX-RX (RX)	10 cm : n/a 20 cm : 4 30 cm - : 2	10 - 20 cm : n/a 30 - 60 cm : 3 70 cm - : 2	10 - 30 cm : n/a 40 cm - : 2	10 - 30 cm : n/a 40 cm - : 2	10 - 20 cm : n/a 30 - 40 cm : 4 50 cm - : 3	10 - 30 cm : n/a 40 - 70 cm : 4 80 cm - : 3	10 - 60 cm : n/a 70 cm - : 3	10 - 70 cm : n/a 80 cm - : 3
TX-RX (TX)	1			2				
RX-RX	2				3			

TABLE III
IMPACT OF ACI FOR DIFFERENT SCENARIOS AND CONFIGURATIONS IN THE 5 GHz ISM BAND. SHOWN IS THE CHANNEL SPACING.

residing on the MAC and routing layer were proposed [1]. The majority of them use 802.11 as physical/MAC layer.

It is important to note that the benefit of a multi-channel protocol heavily depends on the number of available orthogonal channels; the greater the number the higher the benefit from multi-channel protocols. However, our results showed the existence of only a few orthogonal channels. Moreover, the majority of multi-channel proposals require multi-radio systems. However, due to space constraints the spatial separation between radios is very small resulting in a high effect from ACI which means that even fewer orthogonal channels are available. As an example, in the 2.4 GHz band we were not able to find more than 1 orthogonal channel.

Furthermore, the current development trend (e.g. upcoming IEEE 802.11ac [23]) is to combine even more channels already on the PHY layer in order to increase link capacity (e.g. 160 MHz in IEEE 802.11ac) thus leaving no room for multi-channel protocols at the MAC and routing layer. Thus, we believe that multi-channel research on the MAC or routing layer is less important.

B. Promising Research Areas

In the following we present 6 research directions that we believe that they are promising.

a) Adjacent Channel Interference: Efforts must be made to further reduce the energy bleeding over to neighboring channel and thus reducing the adverse effect from ACI. This is especially vital for multi-radio systems where a node is equipped with multiple radios. Because of the small spatial separation of the radios the influence from ACI is very high. The problem can be solved by two approaches: (i) the use of better signal filtering or (ii) my using novel adjacent channel interference-cancelation techniques like the one proposed in [24].

b) Coexistence with Legacy Devices: The current trend is the continued merging of channels already at the physical layer. In 802.11n and 802.11ac up to 2 and 8 channels can be merged together, respectively. Our results show that ACI leads to an increase of hidden and exposed terminal problems. Very wide channels (e.g. 160 MHz in 802.11ac), by contrast, are very vulnerable. The impact should therefore be examined in great detail.

c) Hidden and Exposed Terminal Problem: The number of hidden and exposed terminal problem increases significantly due to ACI when multi-channel protocols are used on overlapping channels. We have to think about solutions how to solve these problems. Note, that the hidden terminal problem cannot be tackled by the use of RTS/CTS exchange. This is because in general an RTS or CTS packet cannot be received on a neighboring channel which is however necessary in order to decode the included NAV. So a different type of channel reservation scheme which respects the impact from ACI explicitly is required.

d) Analytical Models: Analytical models of MAC behavior are important for understanding the wireless performance. However, most models do not take ACI into account.

e) Power Control: Through an intelligent adaptation of transmit power (power control) the number of orthogonal channels can be increased significantly. This is particularly important for the case of multi-radio systems were power control is the only available simple solution to increase the number of orthogonal channels.

f) Explicit Link Scheduling: Given our results that ACI increases the possibility for hidden an exposed terminal problems it appears that an explicit MAC layer link-scheduling [25] is more promising than a CSMA protocol like 802.11. Both problems can be easily solved with such a scheme. This is particularly of great interest for multi-radio-systems where the exposed terminal problem results from the carrier sensing on neighboring channels.

VI. CONCLUSION

We have analyzed the adverse effects of Adjacent Channel Interference (ACI) on 802.11 with a focus on the new 802.11n standard. When using overlapping channels ACI causes problems that are related to the Carrier Sensing (CS) mechanism in 802.11 namely variants of the well known hidden as well as exposed terminal problem. For the case of two nearby transmitters the CS is too restrictive preventing concurrent transmissions and thus reducing the spatial reuse in the network. In the event that a receiver and a transmitter are located close to each other the CS is too optimistic causing the weak incoming signal at the receiver to get corrupted by the ACI from the strong outgoing signal and thus wasting radio resources. Both problems are especially severe in multi-radio systems, where the radios are separated by only a few centimeters.

The upcoming 802.11n standard contains lots of amendments. The most important modifications having an impact on ACI related problems are the use of wider channels (40 MHz), the increased number of OFDM data subcarriers which reduces the number of guard (null) carriers as well as the improved filtering of the OFDM signal compared to 802.11a/g legacy devices.

In the main part we presented results from extensive measurements showing the impact of ACI on three different scenarios for different spatial spacings between the radios, channel width (20/40 MHz) and RF band (2.4 vs. 5 GHz). Our objective was to determine the number of orthogonal channels. In a multi-radio system with a small spatial spacing between the radios the results were poor. From the 11 channels available in 2.4 GHz as well as the 5 analyzed channels in 5 GHz we were not able to find more than 1 orthogonal channel. The adverse effect of ACI can be reduced in two ways. First, by increasing the spatial separation between the radios; a spacing of less than 1 meter already improves the situation significantly, e.g. 40 cm are sufficient to get 2-3 orthogonal 20 MHz channels in the 2.4 GHz band depending on the transmission power. A distance of 90 cm is also sufficient so that a 40 and a 20 MHz channel do not interfere with each other. In the 5 GHz a spatial separation of 70 cm and channel spacing of 3 are sufficient to run two 40 MHz channels independently. However, increasing the spatial separation between the radios is not an option for multi-radio systems where the spatial spacing between the radios cannot be increased due to space limitations. Another option to overcome ACI is the reduction of the transmit power (power control).

Furthermore, we discussed the impact of our results on current research fields. Here we identified promising research areas as well as research directions where we think that they have only little prospects. Our analysis revealed that 802.11 is an inappropriate protocol for multi-channel MAC/routing protocols based on multi-radio systems where an explicit MAC layer link-scheduling is more promising.

References

[1] J. Mo, H.-S. W. So, and J. Walrand, "Comparison of multichannel MAC protocols," *IEEE Transactions on Mobile Computing*, vol. 7, pp. 50–65, January 2008.

[2] J. Nachtigall, A. Zubow, and J.-P. Redlich, "The impact of adjacent channel interference in multi-radio systems using ieee 802.11," *IWCMC '08.*, 2008.

[3] "IEEE Standard for Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput," pp. c1–502, Oct. 2009. [Online]. Available: http://dx.doi.org/10.1109/IEEESTD.2009.5307322

[4] A. Adya, P. Bahl, J. Padhye, A. Wolman, and L. Zhou, "A multi-radio unification protocol for IEEE 802.11 wireless networks," in *BROADNETS'04: Proceedings of the First International Conference on Broadband Networks*. Washington, DC, USA: IEEE Computer Society, 2004, pp. 344–354. [Online]. Available: http://portal.acm.org/citation.cfm?id=1032846

[5] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *MobiCom'04: International Conference on Mobile Computing and Networking*, 2004, pp. 114–128.

[6] J. Robinson, K. Papagiannaki, C. Diot, X. Guo, and L. Krishnamurthy, "Experimenting with a Multi-Radio Mesh Networking Testbed," in *WiNMee'05: Proceedings of the First Workshop on Wireless Network Measurements*, Riva del Garda, Italy, April 2005.

[7] K. Chebrolu, B. Raman, and S. Sen, "Long-distance 802.11b links: performance measurements and experience," in *MobiCom'06: Proceedings of the 12th annual international conference on Mobile computing and networking*. New York, NY, USA: ACM Press, 2006, pp. 74–85. [Online]. Available: http://portal.acm.org/citation.cfm?id=1161089.1161099

[8] C.-M. Cheng, P.-H. Hsiao, H. T. Kung, and D. Vlah, "Parallel use of multiple channels in multi-hop 802.11 wireless networks," in *MILCOM'06: Military Communications Conference*, October 2006.

[9] S. Liese, D. Wu, and P. Mohapatra, "Experimental characterization of an 802.11b wireless mesh network," in *IWCMC'06: Proceedings of the 2006 International Wireless Communication and Mobile Computing Conference*. New York, NY, USA: ACM Press, 2006, pp. 587–592. [Online]. Available: http://portal.acm.org/citation.cfm?id=1143666

[10] K. Ramachandran, I. Sheriff, E. M. Belding, and K. Almeroth, "A multi-radio 802.11 mesh network architecture," *Mobile Networks and Applications (MONET), Special Issue on Advances in Wireless Mesh Networks*, 2008.

[11] P. Fuxjäger, D. Valerio, and F. Ricciato, "The myth of non-overlapping channels: interference measurements in IEEE 802.11," in *WONS'07: Fourth Annual Conference on Wireless on Demand Network Systems and Service*, 2007, pp. 1–8. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4142700

[12] C.-M. Cheng, P.-H. Hsiao, H. T. Kung, and D. Vlah, "Wsn07-1: Adjacent channel interference in dual-radio 802.11a nodes and its impact on multi-hop networking," in *GLOBECOM'06: Global Telecommunications Conference. IEEE*, San Francisco, CA, USA, 2006, pp. 1–6. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4151130

[13] V. Shrivastava, S. Rayanchu, J. Yoon, and S. Banerjee, "802.11n under the microscope," *Internet Measurement Conference '08*, 2008.

[14] S. Gollakota and D. Katabi, "Zigzag decoding: Combating hidden terminals in wireless networks," *SIGCOMM*, 2008.

[15] P. Karn, "MACA – a new channel access method for packet radio," in *ARRL/CRRL Amateur Radio 9th Computer Networking Conference*, Sep. 1990, pp. 134–140.

[16] M. Vutukuru, K. Jamieson, and H. Balakrishnan, "Harnessing exposed terminals in wireless networks," in *NSDI'08: Proceedings of the 5th USENIX Symposium on Networked Systems Design and Implementation*. Berkeley, CA, USA: USENIX Association, 2008, pp. 59–72. [Online]. Available: http://portal.acm.org/citation.cfm?id=1387594

[17] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Prentice Hall PTR, December 2002.

[18] P. J. Husted and W. J. McFarland, "Method and apparatus for selective disregard of co-channel transmissions on a medium," *Atheros Communications Inc.*, 2004.

[19] T. Huehn, R. Merz, and C. Sengul, "Joint transmission rate, power, and carrier sense settings: An initial measurement study," *Technical Report*, 2010.

[20] M. Gast, *802.11 Wireless Networks: The Definitive Guide, Second Edition*. O'Reilly Media, Inc., 2005.

[21] IEEE 802 LAN/MAN Standards Committee, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specificationsAmendment 1: High-speed Physical Layer in the 5 GHz band. IEEE Standard 802.11a," 1999.

[22] A. Zubow and R. Sombrutzki, "Evaluation of a low-cost ieee802.11n mimo testbed," Tech. Rep., 2011. [Online]. Available: http://sar.informatik.hu-berlin.de/research/publications/SAR-PR-2011-12/HWL2011_TechnicalReport_.pdf

[23] "Ieee p802.11 wireless lans, proposed tgac draft amendment," Tech. Rep., 2011. [Online]. Available: http://mentor.ieee.org/802.11/dcn/10/11-10-1361-03-00ac-proposed-tgac-draft-amendment.docx

[24] R. H. Morelos-Zaragoza and S. Kuruba, "An adaptive adjacent channel interference cancellation technique," *Faculty Publications*, vol. 32, 2009.

[25] L. Bao and J. J. Garcia-Luna-Aceves, "Distributed dynamic channel access scheduling for ad hoc networks," *J. Parallel Distrib. Comput.*, vol. 63, pp. 3–14, January 2003. [Online]. Available: http://dl.acm.org/citation.cfm?id=782546.782548