

# Impact of Adjacent Channel Interference on Performance of Multi-Radio Multi-Channel Mesh Networks

## Case Study Final Report



# Impact of Adjacent Channel Interference on Performance of Multi-Radio Multi-Channel Mesh Networks

Peter Dely, Marcel C. Castro, Andreas J. Kassler<sup>1</sup>

## Abstract

In multi-radio wireless mesh networks (WMNs) several radios can operate within one node simultaneously on different channels. Due to frequency selective fading and varying output powers of WLAN cards the received signal strength on channels in the U-NII band can differ by several dB. Furthermore, power leakage from neighboring channels in the frequency spectrum can cause adjacent channel interference (ACI). Using a IEEE 802.11a testbed, we experimentally evaluate the achievable throughput of a multi-radio mesh network in a string topology under the impact of ACI and channel heterogeneity. Our results show that for low PHY rates the channel separation is a good indicator for throughput. However, for high PHY rates the propagation properties of a specific channel also need to be considered. Based on the results we provide recommendations for designing channel assignment algorithms for IEEE 802.11-based WMNs.

## Index Terms

Performance Evaluation, Testbed, Interference

## 1 Introduction

Wireless mesh networks are multi-hop wireless networks, in which mesh points wirelessly relay traffic on behalf of others and by that form a wireless backbone. Typical application scenarios are wireless broadband access, public safety and the extension of WLAN hotspots. Recently, vendors have started to equip mesh points with several wireless cards to allow parallel transmissions on different channels. If the channels are orthogonal and are assigned such that the interference in the network is minimized, this can greatly improve the network capacity. Common assumptions for designing channel assignment schemes for IEEE 802.11 mesh networks are orthogonality of certain channels, the homogeneity of channels and a stable propagation behavior over long time spans. Along with the increased deployment of mesh testbeds, it has been recognized that those assumptions do not hold in reality. [1] and [2] performed extensive measurements in 802.11-based wireless mesh networks and argue that channels are not homogeneous. Their experiments show that for a single link different channels may provide different link qualities depending on the propagation environment. Thus, it is necessary to select properly the set of right channels for the links. Also, [1] presents measurements that show how the link quality varies on a large time scale.

IEEE 802.11a theoretically has 11 to 13 non-overlapping channels (depending on the regulatory domain). However, out-of-band radio-leakage leads to adjacent channel interference (ACI), which may degrade performance significantly [3]. Main reasons for ACI are wireless transceivers, which use imperfect filters to attenuate out-of-channel radiation. As a consequence, out-of-channel signal of nearby frequencies may leak into the desired band. For example, in IEEE 802.11a the signal power is not confined to the channel core bandwidth of  $\pm 11$  MHz relative to the center frequency, but some parts are spread across a  $\pm 30$  MHz band. Such overlapping of the spectrum mask of neighboring channels leads to considerable interference between radios transmitting and receiving on adjacent channels in close physical proximity. According to [3] an increased distance between the receiver and the transmitter antenna can reduce the impact of ACI. More recently, [4] and [5] investigated the relation between ACI and transmission powers in an IEEE 802.11a testbed. [6] characterized the influence of board cross-talk and ACI.

The joint effects of ACI, PHY rate selection and channel heterogeneity are crucial for channel assignment performance. Previous works have only studied those effects individually, which might be

---

<sup>1</sup> Peter Dely and Andreas J. Kassler are with Karlstad University, Universitetsgatan 2, 651 88 Karlstad, Sweden (e-mail: peter.dely@kau.se and kassler@ieee.org).

insufficient in the scope of channel assignment. The key contribution of this paper is the study *of the joint effects* of PHY rate, channel heterogeneity and the time varying nature of the wireless channel and their relation to channel assignment. Throughout testbed measurements, we have seen that channel separation might work as a good predictor for low PHY rates, while for high PHY rates the channel heterogeneity and received signal strength (RSS) of the individual links play an equally important role in the throughput performance of wireless mesh networks.

The rest of the paper is structured as follows: Section 2 describes the measurement setup. Section 3 investigates the impact of channel heterogeneity in a single-hop scenario. Section 4 considers a multi-hop case, in which ACI is present. Section 5 provides a list of recommendation for channel assignment and Section 6 concludes the paper.

## 2 Measurement Setup

The experiments were performed on the KAUMesh indoor wireless multi-radio multi-channel mesh testbed, which is deployed at Karlstad University [7]. The testbed is built from mesh nodes mounted on the ceiling of the computer science department. The nodes are based on Cambria GW2358-4 boards and Intel IXP435 XScale CPUs, running Linux 2.6.22 and MadWIFI 0.9.4. Each node is equipped with three mini-PCI 802.11a/b/g Atheros cards (AR5212 chipset), of which one or two were used for the experiments (labeled  $A_1$ ,  $B_1$ ,  $B_2$ ,  $C_1$  in Figure 1). The antennas are linearly polarized and omni-directional with 3.6 dBi gain. The measurements were carried out in the U-NII low- and mid-band of IEEE 802.11a (channels 36, 40, 44, 48, 52, 56, 60 and 64), which are not used by the campus WLAN. By sniffing the wireless channel we also made sure that no other external interference was present along the experiment.

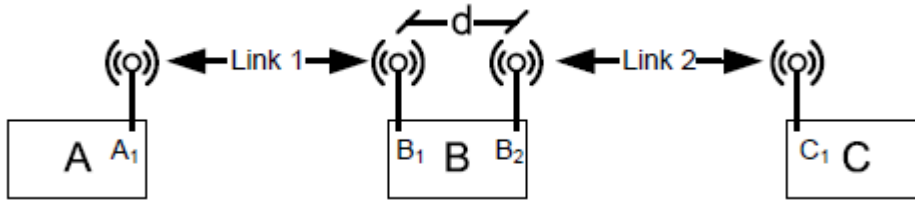


Figure 1: Measurement Setup

For all measurements, we used the simple topology showed in Figure 1. Link 1 ( $A_1 - B_1$ ), is placed in line-of-sight with no obstacles, while in link 2 ( $B_2 - C_1$ ), the nodes are separated by an office wall. The distance between the nodes A-B and B-C is approximately 10 meters each, and the antenna distance between  $B_1$  and  $B_2$  is 20 cm. For all tests (if not stated otherwise) the sending powers were set to 14 dBm and the traffic type was backlogged UDP traffic with 1470 byte datagrams and each data point is an average of 60 seconds measurement.

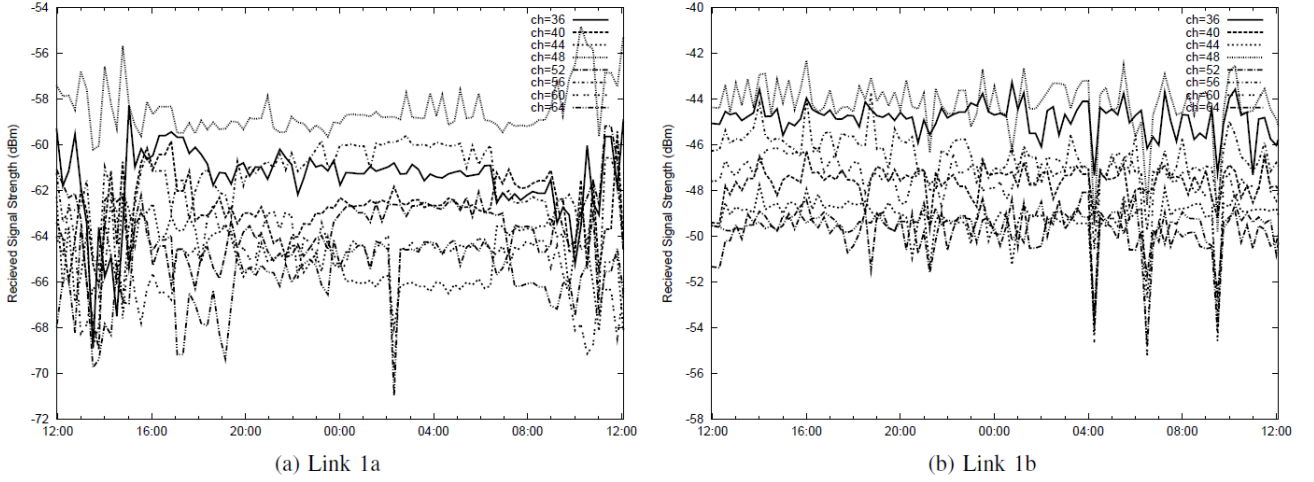
### 3.1 Signal Strength Variations between Channels

We first measured signal strength variations along the frequency spectrum and time. In these experiments node A transmitted 200 UDP datagrams per second for 10 seconds in multicast mode (to avoid MAC layer retransmissions) at PHY rates of 6, 36 and 54 Mbit/s. Node B captured all frames in RF-monitor mode. Link 1a and 1b both denote the link between node A and B, but in link 1b nodes A and B were tilted by  $90^\circ$  while maintaining the overall antenna orientation. Each test was carried out for channels 36-64. The experiment repeated every 15 minutes over several days. Figure 2 depicts the received signal strength over 24 hours (starting at 12:00 noon) for links 1a and 1b.

The following observations are noteworthy:

1. By tilting nodes A and B (changing link 1a to 1b), the link quality drastically changed. While for link 1a signal strengths of as low as -70 dBm were recorded, the weakest signals in link 1b were -55 dBm.
2. For link 1a, there are two intervals: day (approx. 6:00-18:00) and night. The signal strength during night is much more stable than during day hours.

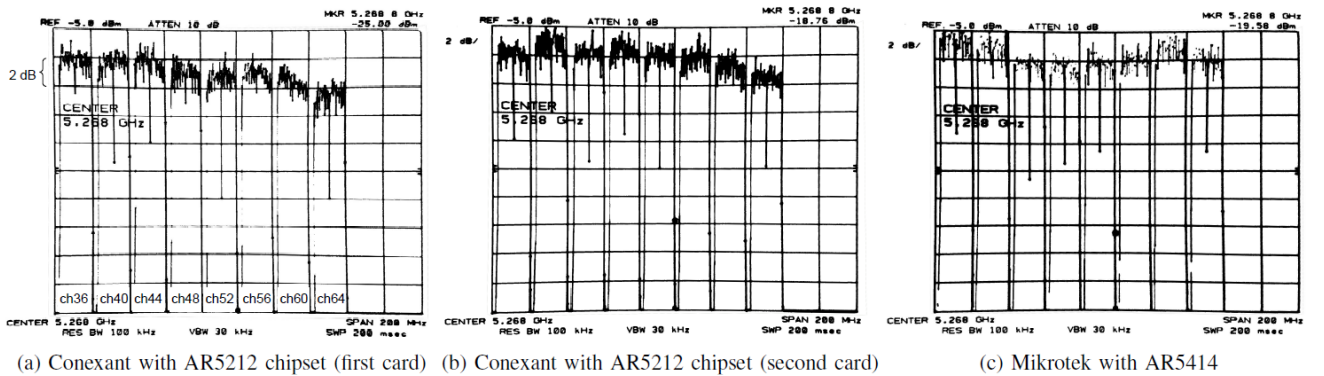
3. For a given link, the signal strength on two channels differs. During the night the signal strength of the strongest (ch 48) and the weakest channel (ch 44) on link 1a differs on average by 7 dB, while during the day the difference can be up to 14 dB.
4. Channels, which are good on link 1a, are not necessarily good on link 1b. E.g. taking the average RSS over 24 hours, channel 60 is the 7th best channel (out of 8) on link 1a, while it is the 4th best on link 1b.



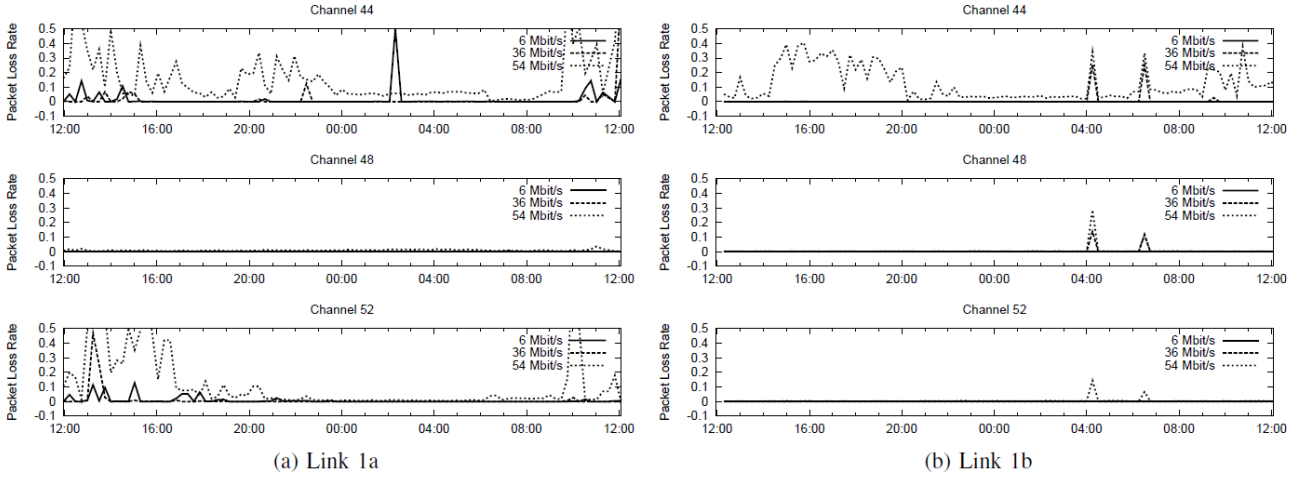
**Figure 2: Signal strength for channels 36 to 64 during 24 hours**

The first observation can be attributed to fading effects, which can cause large signal strength variations, even if the antenna is moved only by a fraction of a signal wavelength. The second observation is harder to explain. Potential sources of the high variability during the day time are the movement of people, as well as lightning, air conditioning, etc. Interestingly, link 1b, which was measured at the end of the semester, when fewer students are present, shows lower variability.

Possible explanations of the third and the fourth observation are different output powers on different channels, frequency selective antenna gains and fading effects. We analyzed this closer by measuring the output power spectral density at the sender for every possible channel using three wireless cards of two different manufacturers, by directly connecting a HP 8566B spectrum analyzer to the WLAN cards. With each card we transmitted data on channels 36 to 64 (10 sec per channel) and recorded the output in MAX-hold mode using the settings specified in clause 17.3.9.2 of [8]. Figure 3 shows the peak output powers of the experiment where each column represents one channel (starting from 36 at the left). The output powers of the two cards from the same manufacturer differ up to 3 dB (e.g. between channel 36 and 64, and channel 40 and 64 for the first and second card respectively). Figure 3c) presents the output power of the other manufacturer, showing a different pattern with a difference of maximum 2 dB. For all cards, the output power distribution of the channels appears random, not even giving the same pattern for the same card manufacturer and chipset. In contrast to [9], we do not find that the channels on the border of a band have a slightly lower output power than the one in the middle of a band.



**Figure 3: Output power for channels 36-64**



**Figure 4: Packet loss rate during 24 hours for 6, 36 and 54 Mbit/s PHY**

Measurements with a vector network analyzer, which outputs a signal on one antenna and measures the received signal strength on a second antenna, showed that our antennas have similar gains over the specified band. Also, considering that channel 44 has weak signal strength, while the next channel (48) has the highest, frequency selective antenna gains are an unlikely explanation for the difference between the channels.

Tilting nodes A and B by  $90^\circ$  (turning link 1a into link 1b) results in a different propagation environment, while other factors such as the WLAN cards remain unchanged. Moving the nodes also changed the order of the channels, making some good channels weak and vice versa (observation 4). Thus, we conclude that the propagation environment is one key factor for explaining the differences between the channels.

### 3.2 Packet Loss Variations between Channels

Different RSS figures result in different packet loss rates. Figure 4 shows the packet loss rate (multicast, without MAC-layer retransmissions) for link 1a and 1b over 24 hours for the 6, 36 and 54 Mbit/s PHY rates. With the strongest channel on link 1a, channel 48, there is almost zero packet loss for all PHY rates. On the weaker channels 44 and 52 in particular the 54 Mbit/s PHY rate can result in considerable packet loss, especially during day hours. On link 1b, which has much higher RSS figures than link 1a, there is packet loss especially on channel 44 at 54 Mbit/s. The 6 Mbit/s PHY rate is more robust and can be successfully decoded even at lower signal strengths. Thus, the packet loss is lower for this PHY rate. Opposite to that, higher PHY rates are more susceptible to signal variations, leading to higher packet loss.

The results show that even in absence of external interference, two channels can have different packet loss rates and consequently different throughputs. This leads naturally to the question, what happens in the presence of external interference e.g. generated by transmissions on adjacent channels.

## 4 Multi-Hop Measurements

### 4.1 Impact of ACI under Different Sending Powers



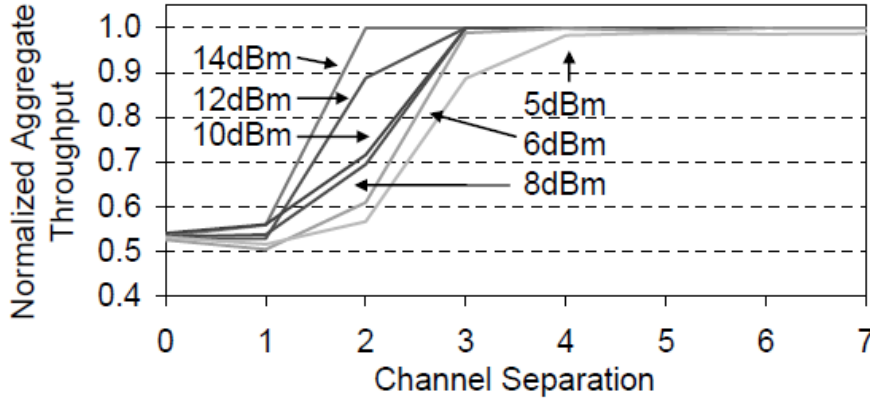


Figure 5: Impact of ACI under different link qualities normalized to the throughput of 10903 kbit/s (PHY rate 6 Mbit/s)

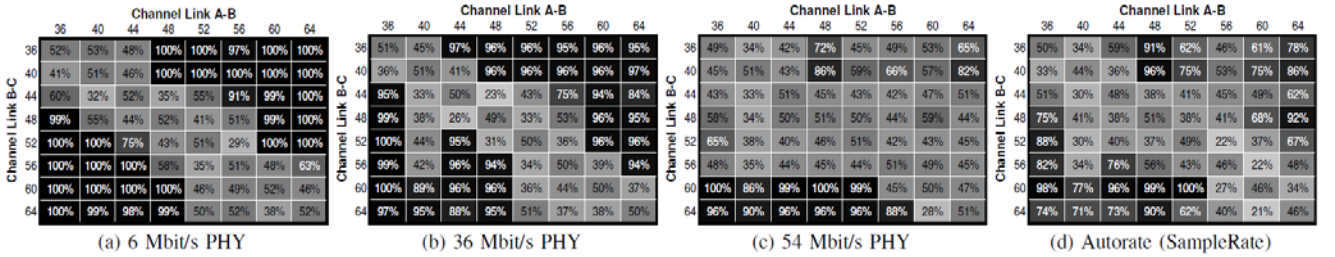


Figure 6: Throughput A-C for different channel combinations (20 cm antenna distance)

We start by investigating the relation between ACI, link quality and achievable throughput. For this scenario, we transmitted backlogged UDP traffic in multicast-mode from nodes A to B and from B to C at a PHY rate of 6Mbit/s. By varying the sending power at node A we simulated different qualities for the link 1. The sending power is chosen such that link 1 always obtains full throughput, if link 2 is not transmitting simultaneously. The channel on link 1 was fixed to 36 and the channel on link 2 varied from 36-64. Channels 36 and 40 yield a channel separation of 1, channels 36 and 44 a channel separation of 2, and so on. Since the sending power of the interferer  $B_2$  remains unchanged, the level of interference at the receiver  $B_1$  is kept the same, while the received signal strength of link 1 is reduced by decreasing the sending power of transmitter  $A_1$ .

Figure 5 depicts the normalized aggregated throughput for different sending powers. The values are normalized to the maximum value of all tests. The figure shows that if the signal quality of link 1 is strong enough (14 dBm), we achieve channel orthogonality while using a channel separation of 2 (ch 36 and 44). However, with a reduced sending power of 5 dBm, the signal on link 1 is weak, which gives channel orthogonality only with a channel separation of 4 (ch 36 and 52). If we analyze the throughput on both links separately, we can see that link 2 always get full throughput, while the throughput of link 1 decreases when reducing the sending power. The difference in throughput between the two links is due to the use of two independent multicast flows. Here, the throughput degradation occurs on link 1 as the ACI contributes to the interference level at the receiver  $B_1$ , leading to a low signal to interference plus noise ratio (SINR) and consequently high packet loss.

## 4.2 Impact of ACI for fixed PHY Rates

In the previous section, multicast traffic was transmitted independently at node A and B. There was no traffic forwarding. In a typical mesh scenario however, unicast traffic traversing several hops with different PHY rates is more common. An interesting question is how the throughput behaves for such traffic type, different PHY rates and channel separations.

In the next set of experiments we evaluated all possible assignments of channels of the U-NII low- and mid-band of IEEE 802.11a with different PHY rates. We performed those tests during the night in order to avoid high fluctuation of link quality. We also vary the antenna distance of  $B_1$  and  $B_2$  and the node positions (link 1a and 1b) and performed the tests on different links and the U-NII upper band.

Due to space limitations we only present the results for 6 Mbit/s, 36 Mbit/s, 54 Mbit/s, and auto rate (using SampleRate [10]) for an antenna distance of 20 centimeters and link 1b.

Figure 6 shows the throughput of an UDP stream from node A to C via B under different channel assignments with 20 cm antenna distance and packet size of 1470 bytes. The values are normalized to the maximum value obtained of all measurements of the particular PHY rate (6 Mbit/s - 5226 kbit/s, 36 Mbit/s - 26063 kbit/s, 54 Mbit/s - 35474 kbit/s, and SampleRate - 33611 kbit/s). As expected, for the case where the links operate in the same channel (e.g. channel combination 36/36, 40/40, etc.), the channel capacity is shared among both links and a throughput between 49% and 52% is achieved.

With a 6 Mbit/s PHY rate, a channel separation of 2 or 3 is sufficient to achieve 100% throughput in almost all cases. Interestingly, the throughput for a channel separation of 1 is less than if both links share one channel. If both links use the same channel (e.g. 36/36), the carrier sensing of IEEE 802.11 DCF avoids the concurrent transmission of two senders. However, if one transmitter is tuned to channel 36 and the other one to channel 40, carrier sensing fails as the links operate on different channels. In this case the signal energy of the interface  $B_2$  leaking into the band of  $B_1$  causes very strong interference, leading to high packet loss [6]. Compared to the previous results, the channel combination 36/44 does not give full throughput in the unicast scenario. There are two main reasons for that. First, unicast traffic uses MAC-layer ACKs, which can trigger additional carrier sensing and lead to more collision opportunities of DATA and ACK transmissions. Second, the unicast traffic here spans over two hops (A-B-C) and thereby the end-to-end throughput is dependent on the packet loss probabilities of both links.

As the PHY rate increases, the results get less predictable. For example, at 54 Mbit/s PHY rate even a channel separation of 7 does not necessarily give full throughput. We describe the predictability with the coefficient of variation (CV), which is the ratio of the standard deviation to the mean. At 6 Mbit/s PHY rate the CV for possible channel assignments with a distance of 4 (e.g.: 36/52, 40/56, 44/60, 48/64) is 0.004. This indicates that all configurations achieve approximately the same throughput and the performance is very predictable. However, for the same channel separation, the CVs for 36 Mbit/s and 54 Mbit/s are 0.21 and 0.39, implying a higher variability and less predictability. Higher PHY rates use modulation and coding schemes which require a higher SINR for successful decoding, leaving a smaller safety margin. Since the SINR can be low due to the weak signal on some channels and the additional ACI, decoding at high PHY rates might fail, while it is still successful for the same channel combination on a lower PHY rate. Since the RSS is a bad indicator of the packet loss probability [11], it is hard to correlate the throughput results with the RSS values.

It is noteworthy that the results in Figure 5 represent a snapshot of the achievable throughput under the current channel conditions only. Repeating the measurements several times showed that at 36 and 54 Mbit/s PHY rate, the throughput of certain channel combinations varies, so that a certain combination yields high throughput at one time, but low throughput another instance of time. At 6 Mbit/s PHY rate the results were relatively stable over time. Characterizing the variability over time is an interesting aspect, which however falls outside the scope of this paper.

For example, at 54 Mbit/s PHY rate the channel combinations 64/48 and 48/64 yield different throughputs (44% and 100% respectively). Channel 48 has a much higher RSS than channel 64 on link 1b. The comparison of RSS values for the different channels on link 2 shows that channel 64 has a much higher RSS compared to channel 48. This example makes clear that in addition to the ACI caused by a specific channel separation, an important factor is the RSS of the individual links. Moreover, the safety margin for the modulation and coding schemes also need to tolerate the additional ACI.

### 4.3 Impact of ACI with Auto Rate

Many existing mesh deployments use auto rate algorithms, which measure PHY and MAC parameters such as RSS or the frame retry-count and aim to select the PHY rate which maximizes the throughput. We studied the performance of the wide-spread SampleRate (default in MadWIFI)[10]. SampleRate counts frame re-transmissions and reduces or increases the PHY rate after successive erroneous or successful transmissions. The previous results showed, that with some channel combinations, lower PHY rates can result in a higher end-to-end throughput.

The comparison of Figures 6 shows that in most of the cases the autorate does not lead to better results than the best PHY rate. To better understand such behavior, we analyze the channel combination

52/64 in more detail. First, we checked which PHY rates are selected by the algorithm for each link (no contribution of the ACI). In this case, SampleRate selects the 48 or 54 Mbit/s PHY rate for > 96% of the frames at link 1 and 2 respectively. The resulting throughput is 25.2 and 31.5 Mbit/s for link 1 and 2. For the scenario where both links are active at the same time (i.e. node B is forwarding traffic), only 59% of the frames on link 1 and 86% on link 2 are sent with 48 or 54 Mbit/s. Due to the higher influence of ACI, the frames on the first link have a higher error probability. As a result SampleRate selects lower PHY rates on average. Thus, the overall throughput of SampleRate is lower compared to a fixed PHY rate of 54 Mbit/s, since SampleRate is too conservative. For channel combination 52/64, the throughput from A to C is 21 Mbit/s with SampleRate, while it is 24.9 Mbit/s for the fixed rate. Similar to the fixed and high PHY rates, the use of SampleRate does not give predictable behavior either.

## 5 Lessons Learned for Channel Assignment And Future Work

The measurements showed that many of the assumptions underlying current channel assignment algorithms for multi-radio multi-channel wireless mesh networks are questionable in practical deployments. From our results we give the following remarks for designing a practical channel assignment scheme in such networks:

1. Channel separation alone is not a good measure of performance: as shown, the channel separation is not sufficient to predict the impact of ACI. RSS plays an equally important role. Higher PHY rates are in general more susceptible to ACI and much less predictable. Channel assignment and rate adaptation are two related problems, which should be jointly addressed.
2. Channels are not homogeneous: For a given link, the RSS on two channels (even neighboring ones) can differ by as much as 14 dB in our measurements. Also, for two different links, the best channels may differ. The only way to obtain the RSS of a link on a specific channel is to measure it. Due to differences in propagation, fading and card output powers it is not trivial to estimate the RSS of a channel by measuring other channels only.
3. A joint channel assignment and power control technique can be used to mitigate the ACI. However, such solutions may require solving very hard optimization problems which need to ensure network connectivity and might depend on the traffic flows.
4. Throughput at 6 Mbit/s PHY rate is more predictable and less susceptible to environmental factors. Low PHY rates are thus preferable when a controlled evaluation of channel assignment schemes is performed. However, when operating commercial mesh networks fixing the PHY rate to 6 Mbit/s might waste resources. This also motivates the design of joint channel assignment and rate adaption schemes.
5. Channel quality fluctuates over time: Due to the varying nature of the channel, a channel assignment which is performing well now, might perform poor later, leading to two options: either to optimize the network for a worst case or to assign the channels to give optimum throughput for the current situation. Thus, frequent channel assignment leads to signaling overhead and impact on routing.
6. Small changes may have large impacts: Due to fading, small changes in the network, such as moving a node or antenna by several centimeters change the nature of a channel significantly. Environmental factors, such as lightning, people moving or temperature further make the network more unpredictable. Again, either very frequent assignment or worst case optimizations should be considered as design paradigms.
7. Current ACI models are insufficient: Current models of ACI (e.g.: [12], [13] and [14]), which model the ACI as percentage of area overlap in the spectrum masks of the cards do not capture the complexity of the problem. Building channel assignment schemes on top of such models will lead to sub-optimal channel assignments.

In conclusion, we have observed throughout our measurements that in case of time varying channels (e.g. real life environment), channel assignment algorithms need to be improved. Channel separation is not sufficient to predict the impact of ACI on multi-hop wireless mesh networks scenarios. In channels with fast, and often large, variations, adaptive algorithms or optimization to the worst case



should be considered. More measurements should be done to try to characterize different environments and narrow the worst case scenario for better optimization purposes.

## References

- [1] Subramanian, Anand Prabhu and Cao, Jing and Sung, Chul and Das, Samir R. Understanding Channel and Interface Heterogeneity in Multi-channel Multi-radio Wireless Mesh Networks. *Proc. of PAM '09*, 2009.
- [2] Kurth, M. and Zubow, A. and Redlich, J. Multi-channel link-level measurements in 802.11 mesh networks. *Proc. of IWCMC '06*, :937, 2006.
- [3] Cheng, Chen-mou and Hsiao, Pai-hsiang and Kung, H. T. and Vlah, Dario. Adjacent Channel Interference in Dual-radio 802.11a Nodes and Its Impact on Multi-hop Networking. *Proc. of IEEE GLOBECOM 2006*, 2006.
- [4] Robitzsch, Sebastian and Niephaus, Christian and Fitzpatrick, John and Kretschmer, Mathias. Measurements and Evaluations for an IEEE 802.11a Based Carrier-Grade Multi-radio Wireless Mesh Network Deployment. *2009 Fifth International Conference on Wireless and Mobile Communications*, pages 272--278, 2009. IEEE.
- [5] Serrano, Pablo and Bernardos, Carlos J. and de La Oliva, Antonio and Banchs, Albert and Soto, Ignacio and Zink, Michael. FloorNet: Deployment and Evaluation of a Multihop Wireless 802.11 Testbed. *EURASIP Journal on Wireless Communications and Networking*, 2010:1--18, 2010.
- [6] Castro, Marcel C and Kassler, Andreas and Avallone, Stefano. Measuring the Impact of ACI in Cognitive Multi-Radio Mesh Networks. *Proc. of VTC-Fall 2010*, Ottawa, 2010.
- [7] Dely, P. and Kassler, A. KAUMesh Demo. *Proc. of 9th Scandinavian Workshop on Wireless Ad-hoc & Sensor Networks* , 2009.
- [8] IEEE 802.11. IEEE.802.11a-Part 11, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Highspeed Physical Layer in the 5GHz Band. 2003.
- [9] Vijay Raman. Dealing with Adjacent Channel Interference effects in Multi-channel, Multi-interface wireless networks. Master's thesis, University of Illinois at Urbana-Champaign, 2008.
- [10] Robert T. Morris and John C. Bicket and John C. Bicket. Bit-rate selection in wireless networks. Technical report, MIT, 2005.
- [11] Halperin, Dan and Hu, Wenjun and Sheth, Anmol and Wetherall, David. Predictable 802.11 Packet Delivery from Wireless Channel Measurements. *Proceedings SIGCOMM 2010*, 2010.
- [12] Mishra, Arunesh and Shrivastava, Vivek and Banerjee, Suman and Arbaugh, William. Partially overlapped channels not considered harmful. *Proc. of the joint international conference on Measurement and modeling of computer systems*, number 1, pages 74, 2006. ACM.
- [13] Angelakis, Vangelis and Papadakis, Stefanos and Siris, Vasilios and Traganitis, Apostolos and Lab, Networks. Adjacent Channel Interference in 802.11a: Modeling and Testbed Validation. *IEEE Radio and Wireless Symposium (RWS2008)*, number 2, Orlando, Florida, 2008.
- [14] Shrivastava, V. and Rayanchu, S. and Yoonj, J. and Banerjee, S. 802.11N Under the Microscope. *Proc. of Internet measurement conference - IMC*, :105, 2008.

