# Understanding Channel and Interface Heterogeneity in Multi-channel Multi-radio Wireless Mesh Networks


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**Abstract.** Multi-channel multi-radio architectures have been widely studied for 802.11-based wireless mesh networks to address the capacity problem due to wireless interference. They all utilize channel assignment algorithms that assume all channels and radio interfaces to be homogeneous. However, in practice, different channels exhibit different link qualities depending on the propagation environment for the same link. Different interfaces on the same node also exhibit link quality variations due to hardware differences and required antenna separations. We present a detailed measurement study of these variations using two mesh network testbeds in two different frequency bands – 802.11g in 2.4GHz band and 802.11a in 5GHz band. We show that the variations are significant and 'non-trivial' in the sense that the same channel does not perform well for all links in a network, or the same interface does not perform well for all interfaces it is paired up with for each link. We also show that using the channel-specific link quality information in a candidate channel assignment algorithm improves its performance more than 3 times on average.


## 1 Introduction

Wireless mesh networks based on commodity 802.11 radios are good vehicles to provide broadband network coverage at a low cost. Mesh networks, however, suffer from serious interference problems limiting their capacity due to broadcast nature of the wireless medium. A common method to improve capacity is to use multiple orthogonal channels that are already available in the 802.11 standard. The core idea is to limit the interference by using different channels for neighboring links. A network node can use multiple channels in two ways – either it dynamically switches channel on the radio interface for different transmissions, or it adopts a multi-radio solution, where each node has multiple radio interfaces tuned to different channels statically (or even dynamically, but at a longer time scale). Different links use different interfaces and thus different channels. The first method – dynamic channel switching on a single radio interface [2] – has proved practically hard as switching latency could be high in commodity 802.11 radios [3]. Thus, the research community has pre-dominantly focused on the multi-radio solution.

The challenge in this case is to develop techniques for channel assignment, i.e., assigning channels to interfaces, subject to an appropriate optimization criterion, for example, reducing network interference or improving capacity. Since the number of interfaces in a network node is limited, this offers a constraint to the optimization problem. Many papers [7, 9] (and references therein) have been published on this channel assignment problem, offering centralized or distributed solutions, investigating optimality questions, comparing performances, etc. *One singular limitation of all these works is that they all assume that the channels and radio interfaces are all homogeneous.* However in practice, the 802.11 channels vary significantly in Signal-to-Noise Ratio (SNR). Also, different radio interfaces on the same mesh nodes often provide different SNR measures even for the same channel. The goal of this work is to understand and demonstrate the heterogeneity in channels and interfaces via a set of careful measurements on two different wireless mesh network testbeds (802.11g and 802.11a) covering a wide-spectrum of possibilities. We show experimentally that the homogeneity assumptions often lead to very poor channel assignment. We followup the measurements with techniques to incorporate channel-specific link quality information in channel assignment algorithms to improve their performance.

The rest of the paper is organized as follows. In Section 2, we describe the details of our mesh testbeds. We present measurement results to understand channel heterogeneity in Section 3. Section 4 presents measurement results to understand interface heterogeneity in multi-radio mesh networks. We demonstrate how to improve the performance of channel assignment algorithms with channel heterogeneity information in Section 5. Related work is presented in Section 6 and we conclude the paper describing future directions in Section 7.

## 2 Testbeds

The measurements reported in this paper are from two different wireless mesh network testbeds (802.11g and 802.11a) set up in our departmental building as described below. The 802.11g testbed uses 10 Dell latitude D510 laptops each with one Atheros chipset based D-link DWL AG660 PCMCIA 802.11a/b/g card with an internal antenna. The transmit powers are fixed to 15 dBm and data rate to 11 Mbps. Measurements from this testbed were collected on 40 different links on three orthogonal channels 1, 6, 11 (2412, 2437 and 2462 MHz respectively) in the 802.11g band. The 802.11a testbed consists of 13 nodes each of which is a Soekris net4801 [1] single board computer (SBC). The PCI-slot in the SBC is expanded into 4 miniPCI slots using a PCI-to-miniPCI adapter. Four 802.11a/b/g miniPCI wireless cards based on Atheros chipset with external antennas are used in each mesh node. In order to overcome radio leakage problems, we physically separated the external antennas at a distance of about 0.5 meters based on measurements similar to [8]. Otherwise, there was a perceptible interference even among orthogonal channels across interfaces on the same node.[3] The transmit

[3] Even with this setup, we could use only a subset of orthogonal channels without interference. These are 7 channels (channels 36, 44, 52, 60, 149, 157, 165) out of pos-

powers are fixed to 15 dBm and data rate to 6 Mbps. Measurements from this testbed were collected on 78 different links in 13 orthogonal channels (between 5180-5825 Mhz) in the 802.11a band. Note that the 802.11a testbed is relatively free from external interference as there are no other networks operating in this band in the building. However, there are indeed several 802.11g networks in our building. Their influence is impossible to eliminate. We, however, did our experiments in this network during late night and early morning when other active 802.11g clients are unlikely.

All nodes in both the testbeds run Linux (kernel 2.6.22 in laptops and kernel 2.4.29 in the Soekris boxes) and the widely used `madwifi` device driver (version v0.9.4) for the 802.11 interfaces. We used standard linux tools such as `iperf` to send UDP packets on the sender node for each link measured and `tcpdump` on the receiver node running on a raw monitoring interface to capture the packets. This gives us the additional prism monitoring header information such as the received signal strength (RSS), noise, channel and data rate for every received packet.

## 3 Channel Diversity

This section shows the results of our measurement study to understand the heterogeneity in channels due to varying path loss of different frequency bands. In the following, we first show that Received Signal Strength (RSS) of packets in each link is relatively stable in each channel and is a 'good' metric to compare the performance of any given link when using different channels.

### 3.1 Long term variation of RSS

We study a single link in the 802.11a testbed for a *24 hour* period by sending 1000-byte UDP packets at a rate of 100 packets per second. We repeat this experiment on 7 different 802.11a channels for the same link. Figure 1(a) shows the Allan deviation in the RSS values in each of the 7 channels at different time intervals ranging from 100 ms to 10 hours. Allan deviation is used as a metric to quantify the burstiness of variation in any quantity. The median variation is about 1.5 dBm and the 90% variation is about 2.5 dBm in a single channel. The variations are similar across all 7 channels. We see that the variation at different intervals are small considering the minimum granularity of RSS measurements is 1 dBm. This figure shows that in *any given channel*, the variation in RSS value is minimal and sampling RSS values at smaller intervals (in the order of tens of seconds) can be representative of longer measurements. We also see similar results in the 802.11g testbed which are not reported here due to space constraints.

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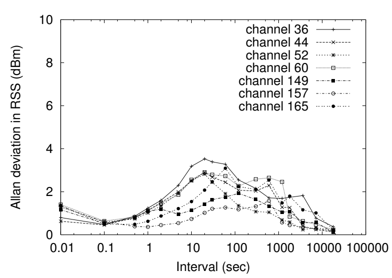
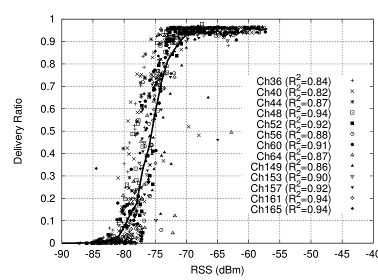
sible 13 orthogonal channels. Thus, we used these 7 channels for channel assignment in Section 5. However, we used all 13 channels to study the channel characteristics in Sections 3 and 4.

### 3.2 Relation between RSS and delivery ratio

Now that we have seen that RSS is relatively stable over long periods of time, next our goal is to show that RSS is a good predictor of link performance in each channel. For this, we studied 78 different links in the 802.11a testbed by sending back-to-back 1000-byte packets in each link using the 13 orthogonal channels for a period of 60 seconds one after another and measured the average RSS value and delivery ratio for each link in different channels. Figure 1(b) shows the relationship between average RSS and the delivery ratio of the links in our 802.11a testbeds. It shows a scatter plot of average RSS vs. delivery ratio of each link for all channels. The interpolations (the dark lines) of the aggregated data are also shown. Visually it appears that the RSS vs. delivery ratio statistics is independent of channels – no definite channel specific pattern emerges. We have also computed the $R^2$ value for each individual channel data with respect to the interpolation (noted in the plots). The $R^2$ values are similar across channels - varying between 0.82–0.94. This shows that RSS is a good predictor of delivery ratio and this relationship is relatively independent of the channel used. Note that delivery ratio (or, throughput) is a commonly accepted performance metric for the upper layer protocols. We observed similar characteristics from measurements in the 802.11g testbed. Thus, we can focus on RSS alone to understand channel and interface specific behavior as this fundamental metric is influenced by the *propagation environment*.




(a) Long term variation of RSS values for a single link in 7 different 802.11a channels.

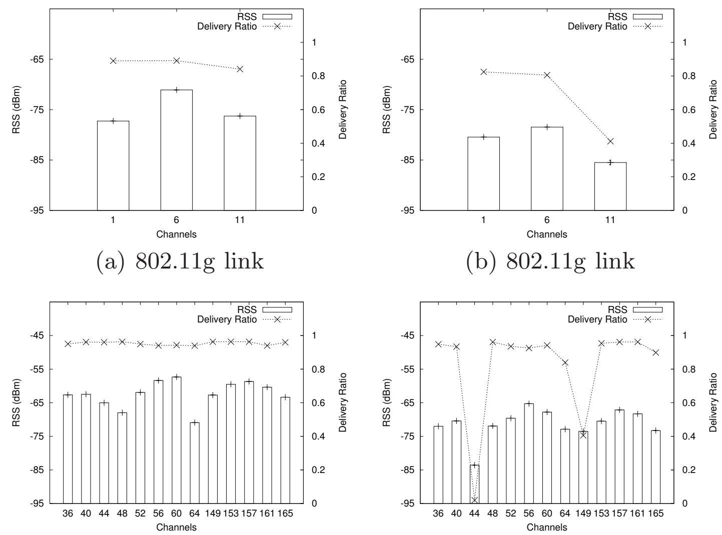



(b) Relationship between average RSS value and delivery ratio in different channels in our 802.11a testbed.

**Fig. 1.** Characteristics of RSS metric.

### 3.3 Link behavior in different channels

Now we look at the average RSS value (with 95% confidence interval) on each channel for two sample links in each testbed. See Figure 2. Figures 2(a) and 2(b) show the performance of two 802.11g links. In both cases, we see considerable




(a) 802.11g link (b) 802.11g link

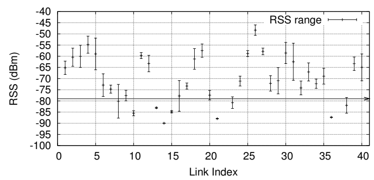
(c) 802.11a link (d) 802.11a link

**Fig. 2.** Variation of RSS and delivery ratio using different channels on sample links in our two testbeds.

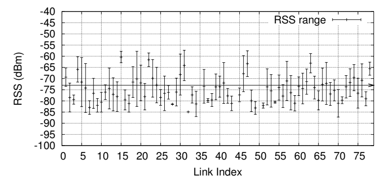
variation in RSS in different channels. In the first case, even though there is variation in RSS, the delivery ratios do not vary much. This is because the RSS values are already quite high. In the second case, we see that the delivery ratio of the link is good in channel 1 and 6 but is quite poor in channel 11. A similar behavior is observed in the 802.11a testbed. See Figures 2(c) and 2(d) for two sample links. These results demonstrate that RSS on a link could be channel-specific and this can impact the delivery ratio significantly.

It is now interesting to study how much variation is there in RSS values for each of the 40 links in the 802.11g testbed and 78 links in the 802.11a testbed. In Figure 3(a) we show the range of variation in RSS value for each link in the 802.11g testbed. The bars show the maximum and minimum RSS value for each link considering all channels. The median RSS range (i.e., the median of the differences between the maximum and minimum over all links) is about 6 dBm and the 90-percentile RSS range is about 12 dBm. Figure 3(b) shows the RSS variation in the 802.11a testbed. In this case, the median RSS range is about 11 dBm and the 90-percentile RSS range is about 18 dBm. This is significantly higher than the variation of RSS in a single channel as noted previously. *Evidently, there are considerable variations in RSS values across channels.* The variation in the 802.11a testbed is higher. This is because the path loss characteristics are frequency specific and the 802.11a band (5180-5825MHz) is much wider compared to the 802.11g band (2412-2462MHz).

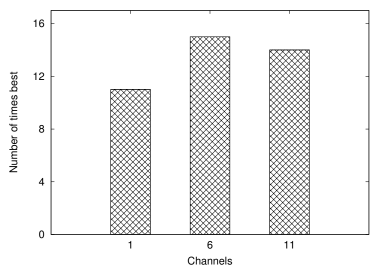
In both the plots, the horizontal arrow shows the RSS threshold values. Note that many links the RSS range crosses the threshold indicating *such links perform poorly in some channels, while performing quite well in some others.*



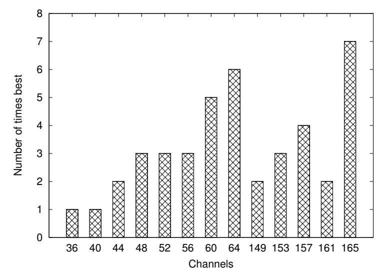

(a) Range of RSS variation in each link in 802.11g testbed across all 3 orthogonal channels.




(b) Range of RSS variation in each in the 802.11a testbed across all 13 orthogonal channels.




(c) Number of times each channel is best based on the RSS values on each link in the 802.11g testbed.




(d) Number of times each channel is best based on the RSS values on each link in the 802.11a testbed.

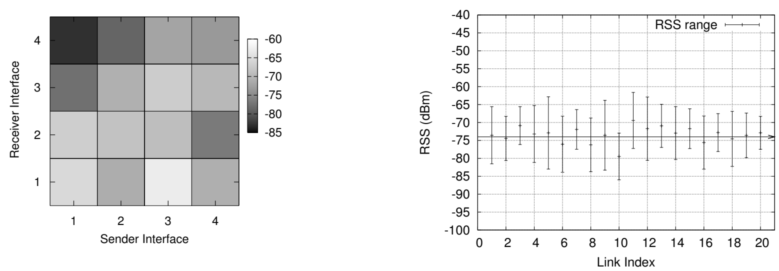
**Fig. 3.** Link behavior across different channels in the two testbeds.

Now, it will be interesting to find out whether there is any one channel that is good for all links. In Figure 3(c) and 3(d), we show how many times each channel is the best based on the RSS values considering all links studied. We see that in both testbeds, there is no clear winner among channels. Each link performs differently in different channels. The RSS values are not correlated with the channel frequency. If this was the case, the channel 36 in the 802.11a band and channel 1 in the 802.11g band should have the best RSS values in all links. Some channels do exhibit better overall performance relative to their peers (e.g., channels 165 and 64 for 802.11a testbed). But generally speaking, any channel could be the best for some link. *This makes it impossible to judge which channels to use for a given link without doing actual measurements on the links.*

## 4 Interface Diversity

For a given link between two multi-radio nodes, the choice of actual radio interfaces to use for this link could impact the link performance. The reason for this is two fold. First, there could be inherent manufacturing variations between the interfaces even though they use the same card model. Second, the antennas for the interfaces need to be situated at a distance to prevent radio leakage issues so that the orthogonal channels do remain orthogonal in practice [8]. This makes the actual distance between different antenna pairs for the same node pair slightly different (noted in Section 2). This issue is more significant in 802.11a as it provides shorter ranges relative to 802.11g. On the other hand, 802.11a is indeed attractive for multichannel work, as it provides many more orthogonal channels.

To understand the variations caused by interface selection, we study 20 links (a subset of the 78 links studied before) in our 802.11a testbed using 16 possible interface pairs for each link. We select the same channel (channel 64, one of the good performing channels) for this measurement on all links in order to isolate the effect of interface selection.




(a) RSS values (in dBm) for 16 possible interface pair combinations on a sample link.

(b) Range of RSS value between different interface pair combinations for each link.

**Fig. 4.** Interface heterogeneity in multi-radio nodes in 802.11a testbed.

Figure 4(a) shows the RSS values on all 16 possible interface pair combinations for a sample link. Here we see that the RSS value varies between -60 dBm to -85 dBm. Considering the RSS threshold (about $-74$ dBm), the link shown here has a very poor delivery ratio when certain interfaces are used (e.g., 1 to 4). However, some other interfaces would have a good delivery ratio (e.g., 3 to 1). *It is also interesting to note that we cannot say that a specific interface has poor performance.* For example, if we consider the interface 1 on the sender node, it has varying performance based on the receiver interface.

In Figure 4(b), we show the range of variation in RSS values between the 16 possible interface combinations for each of the 20 links studied. Each bar shows the maximum and minimum RSS value for each link considering all 16 combinations. Note the significant variation in RSS values among different interface pairs. The median and 90-percentile RSS variation is about 12 dBm and 16 dBm respectively. Also note that most of these ranges straddle the RSS threshold (−74 dBm). This means the delivery performance can indeed significantly vary depending on the interface choices. *A channel assignment algorithm unaware of such variations can easily choose a bad interface pair for a link even though there are better interface pairs that could be potentially used.*

## 5 Channel Assignment Algorithm

In this section, we demonstrate the potential of using channel-specific link quality information in existing channel assignment algorithms to get better performance. For this purpose, we modify the greedy channel assignment algorithm proposed in [9] to use the channel-specific link quality information when assigning channels for links. The greedy channel assignment algorithm assigns channels to *links* [4] in a greedy fashion trying to minimize the overall interference in the network. At the same time it satisfies the interface constraint, i.e., ensures that the number of channels assigned to links incident on a node does not exceed the number of interfaces on the node.

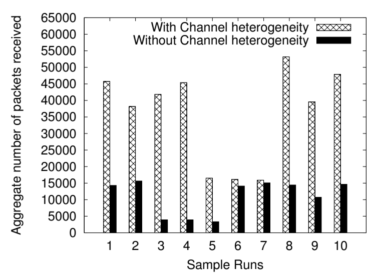



**Fig. 5.** Aggregate number of packets received when a set of 10 links transmit packets simultaneously. Each sample run consists of a different set of 10 links in the network.

The channel assignment algorithm works as follows: Initially, none of the links are assigned channels. The algorithm iterates through each link that is not assigned a channel yet and chooses a feasible set of channels that obey the interface constraint. From this feasible set of channels, it selects a channel that minimizes the overall *network interference* which is modeled using a conflict graph. The algorithm terminates when no further assignment of channels to links can reduce the network interference. Note that among the channels in the feasible set, it is often the case that more than one channel can lead to the minimum interference. Since the algorithm is unaware of possible difference in

[4] Since it assigns channels to links directly, it is difficult (but not impossible) to incorporate the interface-specific information in this algorithm. We consider exploring the use of interface-specific information as a part of our future work.

link quality in different in channels, it chooses one channel arbitrarily. *Note that this is a singular limitation in all channel assignment algorithms in current literature as they do not use channel specific link quality information to make a choice.* In the new version of the greedy channel assignment algorithm, we use the channel-specific link quality information (e.g. RSS on different channels) to make this choice. Given RSS values are relatively stable, short term measurements (one time or periodic) are good enough to estimate the link quality in different channels. These measurements can be done whenever the channel assignments are recomputed. Estimating the periodicity of channel assignment depending on the environment and channel conditions is one of our future work.

In our 802.11a multi-radio testbed, we use 7 orthogonal channels (channels 36, 44, 52, 60, 149, 157, 165) and 4 interfaces in each node to study the performance of the channel assignment algorithm. In Figure 5, we show the performance of the greedy channel assignment algorithm with and without the channel-specific link quality information. We used periodic probes sent at 100 packets per second in each channel for 1 second to measure the link quality in different channels on each link before running the greedy algorithm that uses channel-specific link quality information. The horizontal axis shows 10 different experimental runs. In each run, we send back-to-back UDP packets on 10 randomly chosen links simultaneously. The two versions of the channel assignment are used to assign channels for these 10 links. For each channel assignment, the experiment is run for 60 seconds and the aggregate number of packets received is measured. Note that the channel assignment algorithm using the channel-specific link quality information performs very well in all experimental runs compared to the case when all channels are considered homogeneous. Except in two cases (runs 6 and 7), the improvements are quite substantial - varying between 2-8 times. We noted that in the two cases where performance improvements are marginal, use of channel-specific information did not result in a very different channel assignment. Overall, the average improvement was by a factor of about 3.

## 6 Related Work

There is a growing body of literature that use multiple channels to reduce interference in wireless mesh networks [2, 9, 7]. Many of them use multi-radio solutions [6, 9, 7] (and references therein) to eliminate the need for dynamic channel switching. However, none of these works consider the variations in link quality depending on the channel or interface chosen for communication. Channels are always assumed to be homogeneous and link quality to be independent of interface selection or choice of channel.

Recently, Das et al [4] have observed variation in routing metrics in different channels in wireless mesh networks. However, their work primarily focuses on comparing different routing metrics and understanding their dynamics. In [5], the author has observed variation in link quality in multiple channels when studying interference maps in 802.11 networks. The paper studied one 802.11a link and showed variation in delivery ratio in different channels. Our work quantifies the variation in using different channels and interface pairs using extensive measurements in two different mesh testbeds operating 802.11g and 802.11a bands and using different hardware platforms. We also show that the variations in link quality are not correlated to frequency of the channels. We also experimentally demonstrate that utilizing channel and interface-specific information in channel assignment algorithms improves performance significantly.

## 7 Conclusions

This paper presents a detailed measurement study of channel and interface heterogeneity in multi-radio wireless mesh networks using measurements from two mesh testbeds using different hardware platforms and frequency bands (2.4GHz for 802.11g and 5GHz for 802.11a). We quantify the variation in link quality when using different channels and interface pairs and show that choosing the right channel and interfaces for a link can improve its performances significantly. We also demonstrate that this variation is 'non-trivial' in the sense that same channel does not perform uniformly well for all links, or the same interface does not perform uniformly well for all other interfaces it is paired up with.

All prior channel assignment works in literature ignore this important assumption. We demonstrate how the channel heterogeneity information can be incorporated in an existing channel assignment algorithm to improve its performance. An important future direction of our work is to develop methods to measure these variations efficiently, understand how often they need to be repeated and design channel assignment schemes that take both channel and interface variations into account and come up with efficient solutions.

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