Invited Paper

Journal of Information Processing Systems, Vol.8, No.1, March 2012 http://dx.doi.org/10.3745/JIPS.2012.8.1.001

Indoor Link Quality Comparison of IEEE 802.11a Channels in a Multi-radio Mesh Network Testbed

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Abstract—The most important criterion for achieving the maximum performance in a wireless mesh network (WMN) is to limit the interference within the network. For this purpose, especially in a multi-radio network, the best option is to use non-overlapping channels among different radios within the same interference range. Previous works that have considered non-overlapping channels in IEEE 802.11a as the basis for performance optimization, have considered the link quality across all channels to be uniform. In this paper, we present a measurement-based study of link quality across all channels in an IEEE 802.11a-based indoor WMN test bed. Our results show that the generalized assumption of uniform performance across all channels does not hold good in practice for an indoor environment and signal quality depends on the geometry around the mesh routers.

Keywords—IEEE 802.11a, Indoor Test Bed, Link Quality, Wireless Mesh Networks

1. Introduction

Wireless mesh networks (WMNs) have increased the popularity of wireless networking technologies by providing the lure of wireless infrastructure networks and a promise of ubiquitous high-speed Internet access [1, 2]. At the heart of this promise lies an attempt to provide full capacity of WMNs through improved link utilization by reducing the interference within the network. In order to achieve this objective multi-radio multichannel WMNs have been proposed and evaluated by an increasing number of analytical, simulation and experimental studies [3-15].

These schemes seek to exploit non-overlapping orthogonal channels made available by the IEEE 802.11 WLAN standard [16] to reduce intra-channel interference within the network, thereby facilitating improved link utilization. A common theme linking all these studies together is the unstated assumption that *link performance is consistent across all orthogonal channels*. No distinction is made while selecting one channel over the other based on its quality, excluding the effects of interference, particularly when those channels are from the same frequency range (say 5GHz range used in IEEE 802.11a). In few cases where the difference in link quality across channels is acknowledged, it is assumed that interference is solely responsible for this disparity [17, 18].

The objective of this paper is to experimentally validate whether these assumptions hold true

Manuscript received January 13, 2012; accepted February 8, 2012.
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in an *indoor environment*, where the radio propagation characteristics are different [19, 20]. We conducted a study to measure and compare the link quality of every viable link in an indoor testbed using a metric based on packet delivery ratio. We show that the link quality over the 12 orthogonal channels of IEEE 802.11a is *not consistent, and can not be assumed to be uniform*. We arrive at this conclusion based on the following observations that were made in an interference free environment.

- The channels in the *Unlicenced National Information Infrastructure* (U-NII) upper band (149 – 161) perform significantly worse than the U-NII lower band (36 – 48) and U-NII middle band (52 – 64) channels, in general. This reduces the number of channels that can be used in practice, in most cases. This led us to focus on the quality of the better performing lower 8 channels for the rest of the work.
- Almost all links between mesh routers in the testbed show moderate to high variation in the link quality across the IEEE 802.11a channels.
- The best to worst performing channels for links in the same neighborhood varies considerably, and is unpredictable. That is, the best available channel(s) for each link does not depend solely on the interference and channel utilization in the neighborhood; it is highly sensitive to the building structure, and relative positioning and orientation of the antennae used.

We collected our first set of measurements manually and used this experience to develop an automated program to do the same. Manual measurement of link quality has little value in practice, if we were to utilize link quality information in a dynamic and automated process to configure a WMN. Therefore, we analyze the performance of our automated program with respect to manual data collection and show that its performance matches that of the manual process really well.

The rest of the paper is organized as follows. In Section II, we take a detailed look at the motivation for our study and the background material that helped us with the same. We present the configuration of our testbed, justification for selection of link quality metric and the experimental procedure in Section III. In Section IV, we present our primary experimental study and analysis. The accuracy and validity of results obtained using the script and its importance are analyzed in Section V. Finally, we conclude with an overall summary and final remarks on our findings in Section VI.

2. BACKGROUND AND MOTIVATION

Wireless networking solutions have risen in popularity and usage over the last decade or so, owing largely to the low-cost and high-performance of commercial off-the-shelf (COTS) IEEE 802.11 wireless equipment. The availability of these cheap hardware has encouraged a variety of research and experiments aimed at extending the realms of wireless networking beyond what had been envisaged by the existing standards. One such attempt was conceived to expand Internet access to clients that are multiple hops away from the Internet [21]. This idea was subsequently coined as wireless mesh networking, and has been projected to be used for a lot of other applications, based on providing wireless infrastructure networks that possess the characteristic of rapid deployment, while maintaining its low-cost [1, 2]. One class of such applications is an indoor WMN, that could augment already existing implementations of home and enterprise networks, building automation, medical and health systems, and security surveillance systems [1, 2, 22, 23].

Under the generally accepted terminology, WMNs comprise of Mesh Routers (MRs), Mesh Clients (MCs) and Internet Gateways (IGWs). WMNs provide last mile Internet access to the end user MCs by connecting them to the IGWs via multiple MRs. The IGWs and MRs together make the mesh backbone, which is responsible for multi-hop relaying of packets within the network [1]. Tremendous interest in this area of research has inspired an amendment to the IEEE 802.11 standard, viz. 802.11s, under the patronage of IEEE 802.11 Task Group S, which completed its draft only in 2011 [24]. In this vacuum, 802.11a/b/g became the de-facto standard for WMNs, borrowing ideas from existing research on mobile ad hoc networks (MANETs).

By adapting a technology designed for a different concept, WMNs have been plagued by insufficiencies from its inception. The use of a single wireless channel to ensure connectivity between all in-range MRs proved to be very inefficient due to intra-network interference [25]. The solution to this problem was to use the multiple non-overlapping orthogonal channels provided by the IEEE 802.11 standard; 12 channels in 802.11a and 3 channels in and 802.11b/g respectively [16]. As dynamic and frequent channel switching is shown to be highly ineffective with existing technology [26], the main focus fell on a long-term channel assignment in multi-radio multichannel networks to achieve full capacity of WMNs [18, 27].

The channel assignment problem has been formulated under a variety of assumptions, by a myriad of experimental [6, 11], theoretical [4, 5, 12] and simulation [3, 7-9, 13-15] studies. All these works use the unstated assumption that the orthogonal channels will perform equally well for any given link in the WMN. This is a critical issue, as it has been observed that when link quality is marginal the performance of multi-hop networks drops drastically [28]. Thus, if in reality the link quality between two radios of two MRs differ based on the channel being used, the importance of this information in maximizing the performance of WMNs cannot be overlooked.

With the focus already on the latest high-speed wireless standard, IEEE 802.11n [29]—which operates on frequency bands used by 802.11a (5GHz) and 802.11b/g (2.4GHz)—to be the mainstay of next-generation high speed backhaul WMNs, it is imperative that we fully understand the importance of distinguishing between channels for their link quality.

3. Experimental Setup and Procedure

The results presented in this paper have been obtained using experiments conducted at an indoor WMN test bed. In this section, we describe our test bed, hardware and software configurations, selection criteria for the link quality metric and the methodology used to gather and present data.

3.1 Test Bed Description

For our experiments, we have used an indoor WMN test bed consisting of 9 MRs. This network spans across the 8th floor of the Engineering Research Center (ERC) building, at the University of Cincinnati. In this test bed, the MRs are placed in a chain topology, along four

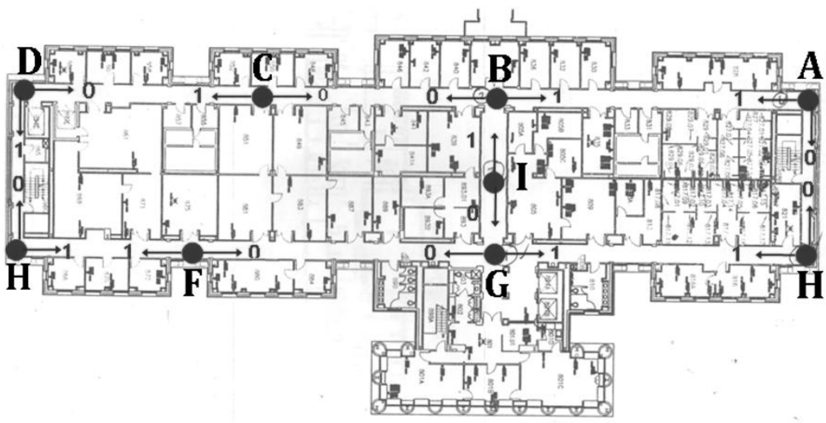


Fig. 1. Mesh Networking Testbed ERC Building

interconnected corridors, making it a rectangle (Fig. 1). Even though we have a larger network in our test bed, which consists of 17 MRs and deployed in an adjacent, but a separate, building, we selected the former for this experiment, as the building design and the MR placements are more uniform, than in the latter. We expected that this test bed–due to its simple and even design–would provide us with predictable performance between each MR-pair, based on the antenna orientation, distance and the line of sight (LOS).

3.2 Hardware and Software Configuration

In our test bed, we use commercial, off-the-shelf (COTS) hardware and free and open source software (FOSS), without any modifications. *The objective is to make our results comparable and applicable to the regular users of IEEE 802.11a/b/g wireless devices in building a WMN.* The hardware and software components used in our test bed are given in Table 1. The MRs are placed above the drop ceiling in the corridor, while the flat panel antennae are suspended by the metal grid supporting the ceiling. This is done such that LOS is also maintained. As shown in Fig. 1, the MRs are labeled A through I. The two wireless cards in each MR are identified as *ath0* and *ath1* by the device driver (madwifi-ng), and we identify the antenna attached to each wireless card as *antenna 0* and *antenna 1*, respectively. In Fig. 1, the direction of the main lobe of each flat panel antenna is indicated by the arrowhead, which is also indicated by the corresponding antenna number.

We used IEEE 802.11a for our experiment. This was done for two reasons. First and foremost, because it provides us with 12 orthogonal channels, as opposed to only 3 such channels in IEEE 802.11b/g. This is the most important reason as our objective was to compare the performance of different channels over a multi-radio multi-channel WMN, and having 12 channels provides a larger basis for a useful comparison. The other reason is that 5GHz band used by IEEE 802.11a is largely unsaturated, compared to the 2.4GHz band used by the much more popular IEEE 802.11b/g wireless devices, as well as other devices like cordless telephones, Bluetooth devices, and even microwave ovens. Though we included 2.4GHz channels in our primary testing phase, we found that there was so much interference, even at night, that there was not a single antenna-pair that could communicate in those channels without any packet loss (data not shown). For all

Table 1. Test Bed Details

Mesh Router	Metrix Mark II (Dual Radio)
Motherboard	Soekris net4826
Wireless Card	Wistron CM9 (2 in each MR)
Chipset	MAC: Atheros AR5213
	PHY: Atheros AR5112
Antenna	HG2458-09P Flat Panel
Frequency Range	2.4 -- 2.5GHz / 5.1 – 5.8GHz
Gain	6 dBi @ 5.125 -- 5.850GHz
Beamwidths	Horizontal: 65^o/ Vertical: 25^o
Antenna Cable	240 series 50ohm coaxial (10ft)
Type	CFD-240 (LMR-240/HDF-240)
Attenuation	0.204dB/ft @ 5800MHz
Operating System	Pyramid Linux 1.0b5
Kernel	Linux 2.6.19.2
Wireless Driver	Madwifi-ng

those reasons, we decided to use IEEE 802.11a for our experiment.

3.3 Selecting the Link Quality Metric

Selecting the right metric to assess the quality of a wireless link is a non-trivial task [30]. However, we limited our choices by enforcing a requirement that the relevant measurements should be easy to obtain using ubiquitous tools. The reasoning behind this was twofold.

- First, we wanted to make sure that our results are compared and analyzed along with results from similar mesh networks. Since there aren't many indoor WMN test beds using IEEE 802.11a in the open literature, we hope that we could inspire similar tests to be done in-door WMNs that are in use, so that proper comparisons could be made.
- Secondly, if we intend to incorporate this data into the channel selection process of WMNs, then accurate yet easy link quality measurements are a primary requirement.

We short-listed, measured and analyzed two link quality metrics in order to select the most suitable for our study.

1. *Signal strength*–also defined as the *Received Signal Strength Indication (RSSI)*–values: Provided by the wireless chipset. We recorded the relevant signal strength values, reported by the *iwlist* program, between each possible antenna-pair across all channels. The wireless interfaces were set to *ad hoc* mode and the transmission power (TxPower) was set at 17dBm throughout the network.
2. *Least Power for Zero Packet Loss (LPZPL)*: Based on the round-trip *packet delivery ratio (RT-PDR).* We defined LPZPL threshold as the lowest TxPower at which an antenna-pair is able to communicate at zero percent packet loss over a given channel. In the instances where the ad hoc cells (IBSS) failed to merge [31], or there were packet losses at maximum TxPower, *"destination host unreachable" (DHU)* or the corresponding packet loss

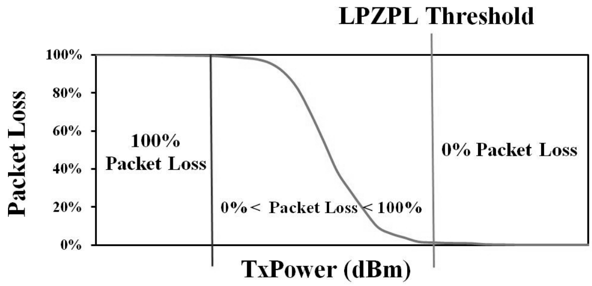


Fig. 2. Least Power for Zero Packet Loss (LPZPL)

were recorded, respectively.

Since our main objective in this study is to compare and contrast the link performance across all the channels in IEEE 802.11a, we were determined to select a link quality metric that reveal lowest level of variability across observed results. Even though the signal strength is easier and faster to obtain, we compared it with the LPZPL, for three reasons.

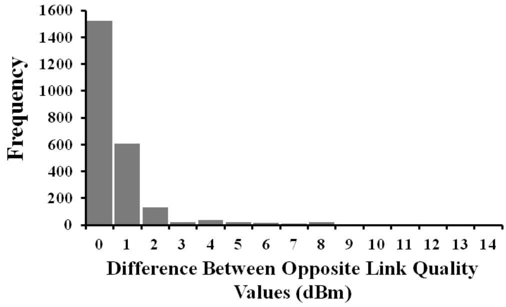
- We wanted to choose the best metric that provides the closest approximation to the quality that we intend to compare viz. link performance.
- PDR is a closer approximation to link performance, though it takes longer to quantify accurately, even in the simplest form we've used in our experiment.
- We wanted to find out the correlation between the two metrics, as there are conflicting claims on the predictability of link performance based on RSSI values (all these studies use the SNR metric derived from RSSI readings) [28, 32, 33].

Even before we compared the two link quality metrics, it was evident from the results that the symmetry of link quality values (i.e., the difference between the link quality values of a link in opposite directions) is significantly better with LPZPL than with RSSI. As illustrated by Fig. 3, the LPZPL values for 64% of the links are exactly similar in both directions, while another 25% differs only by 1 dBm. In contrast, the difference between the RSSI values in opposite directions is spread across a wide range of values.

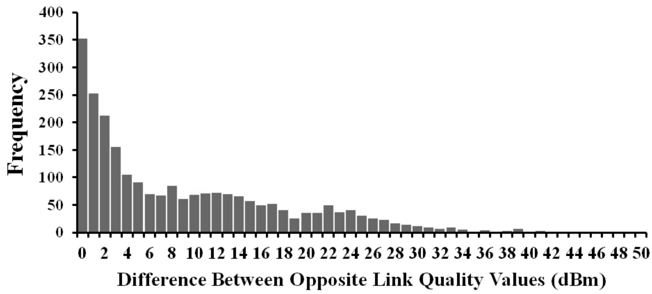
This stability of LPZPL is hardly surprising, given the fact that it is derived from a measurement based on the round-trip data delivery. It was obvious that the significant variations of RSSI values as observed from either end of a link makes it difficult to use RSSI that represents the link performance. However, we continued with our comparison of link quality metrics to get a better idea of the differences between the two.

We compared the results from the two link quality metrics on per antenna-pair basis, as well as, as groups of similarly aligned and placed antenna-pairs. *Signal strength values showed higher variability than the LPZPL threshold values across all results*, including the cases where the latter had zero variability.

We tried to find a correlation between the two, at the least by introducing threshold values to signal strength, so that we could avoid relatively expensive LPZPL measurements. However, the scatter plot between RSSI values and their corresponding LPZPL values (Fig. 4) indicates that for most RSSIs value within the measured range, the corresponding LPZPL value could span

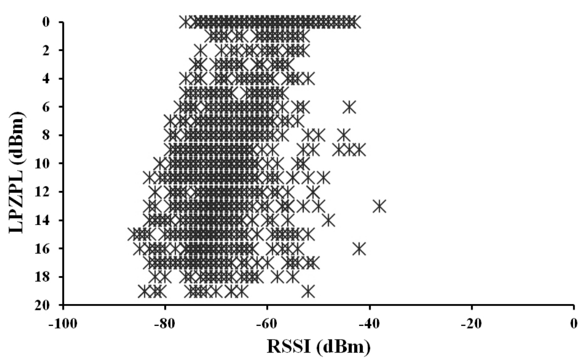


(1) Link Symmetry of LPZPL



(2) Link Symmetry of RSSI

Fig. 3. Symmetry of Link Quality Values



Note: Data in opposite directions are included here as separate entries

Fig. 4. RSSI values vs. corresponding LPZPL values.

from the best to the worst.

Looking at these data from another angle indicates that this apparent lack of correlation is exaggerated by huge variations in the RSSI values for a given link in the opposite directions. However, as shown in Fig. 5, these variations of RSSI values are not reflected by the corresponding LPZPL values. This particular observation confirms that any attempt to find a correlation between the two link quality metrics is a futile exercise.

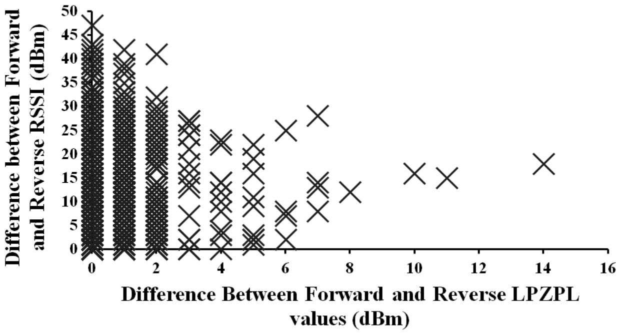


Fig. 5. The difference between LPZPL values of a given link in the two directions vs. corresponding RSSI values

In addition to these results in its favor, we also recognized that LPZPL threshold values could serve a secondary, yet important, purpose towards our ultimate goal of incorporating link quality values in the WMN configuration. That is, the *LPZPL threshold provides the minimum TxPower value required for a successful transmission between each antenna-pair, thereby limiting the interference region created by each link.*

Based on all these observations, we decided to use the LPZPL threshold as our link quality metric.

3.4 Experimental Methodology

The objective of our experiment is to measure the link quality between each viable antenna-pair over all the channels in IEEE 802.11a. As our goal is to study the performance of a WMN backbone, we used the *ad hoc* mode to facilitate communication between each antenna-pair. We measured the RT-PDR at each TxPower level using the *ping* program with its default packet size, and derived the LPZPL threshold values from those data. The transmission rate is kept at the default *auto.* All the experiments are done at night to minimize interference with other wireless networks in the building.

The experiment was conducted in two phases.

- *First phase*: The experiment has been conducted manually, over a period of 3 months. During this phase, we ran the *ping* program for 5,000 iterations at 20ms intervals, between each antenna-pair over each channel, and we recorded the lowest TxPower at which it could communicate at near-zero packet loss. Even though it is a single set of data, we repeated each measurement many times on different days to make sure that we avoid the influence of interference in our data.
- *Second phase*: We used a script to run the experiment and record the data. To improve the accuracy of this automated process of data gathering, we collected three independent sets of data. Using the script, we ran the *ping* program for 3,000 iterations at 5ms internals at each instance. The reduction in the number of iterations and the interval was arrived at after a series of tests in order to expedite the data gathering process, without affecting the outcome.

In the analysis, our aim is to find the best possible link quality between each viable antenna-

Table 2. Extrapolation to allow Packet Loss at Max TxPower

< 5%	Max TxPower + 1 dBm
6% - 29%	Max TxPower + 2 dBm
30% - 79%	Max TxPower + 3 dBm
80% - 99%	Max TxPower + 4 dBm
100% (DHU)	25 dBm*

* to ensure that DHU is above any other value

pair over all the channels. As such, we represent the link quality of a given antenna-pair/channel combination by the lowest LPZPL threshold from the four sets of data (1 manual and 3 automated).

We also incorporated the instances where there were packet losses at maximum TxPower, into the final analysis. Based on our experience from the manual process of data gathering, we came up with an extrapolation table to represent those data points (Table 2).

4. Comparing Link Quality

4.1 Introduction

In the first phase of the experiment, we gather a series of measurements to compare the link quality of all possible antenna-pairs over different channels of IEEE 802.11a. The results from this phase shows that even in the absence of interference, there is a high variability between link qualities across the channels.

There is also a large difference between the link quality plots of each antenna-pair. In an effort to minimize this difference within the group, we grouped together antenna-pairs with similar characteristics, and identified all possible patterns. As such, the results from the first phase were broadly categorized according to the relative orientation of the antennae (e.g., the two antennae facing each other). For the second phase, only the antenna-pairs in categories that could communicate with near-zero packet loss (LPZPL) at the *maximum TxPower* across a wide range of channels were selected. The automated script has been used to obtain three sets of measurements for these antenna-pairs.

Antenna-pairs that have been selected to be compared belong to three categories as follows:

- Both antennae facing each other (facing – facing)
- One antenna facing the other, while the other faces away (facing – opposing)
- Both antennae facing away from each other (opposing – opposing)

The combined results for these selected antenna-pairs are presented in this section.

4.2 Experimental Results

We first analyze the link quality of each channel across the selected antenna-pairs (Fig. 6). The link qualities of all antenna-pairs per channel are bundled together without clearly distinguishing between each pair, as our objective is to identify generic patterns emerging from the results, if any. The main observation is the difference between the link quality over the lower 8

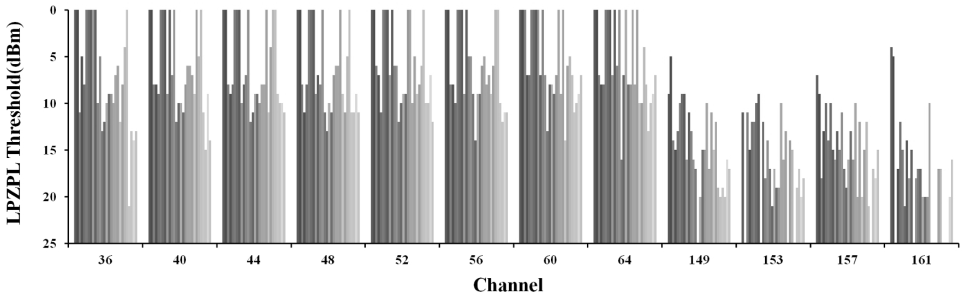


Fig. 6. Comparison of Link Quality across all antenna-pairs for each channel in IEEE 802.11a

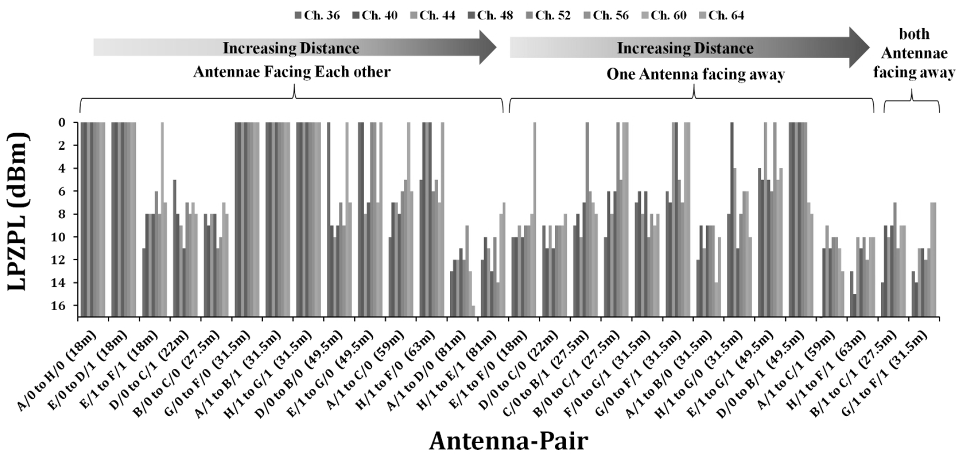


Fig. 7. Comparison of Link Quality across lower 8 channels for each antenna-pair in the three selected categories viz. antennae facing each other, one antenna facing away and both antennae facing away from each other. For each antenna-pair, the link quality of channels 36-–64 are ordered from top to bottom. N/x and M/y in axis labels denotes that the communication is between MR N's antenna x and MR M's antenna y. Distance between the antennae are given in the parenthesis

channels (36—64), as compared to the upper 4 channels (149—161) of the IEEE 802.11a standard. The link quality between an antenna-pair among all such pairs is significantly worse over the upper channels.

Next, we looked at the link quality of each antenna-pair across the channels in Fig. 7. As the link qualities of the upper 4 channels are consistently weaker, we limit our analysis to the results from the lower 8 channels. The antenna-pairs in each category are sorted by increasing the distance between the antennae. The results show only 5 out of 28 antenna-pairs display the best link quality values for all 8 channels (LPZPL at 0dBm). The rest of the antenna-pairs exhibit varying degrees of inconsistency in the link quality values across the channels. Mean and standard deviation of link quality for each antenna-pair are plotted in Fig. 7.

We also measured *outdoor* link quality values between antenna-pairs facing each other at varying distances, with the maximum distance equal to the length of the long corridor of the

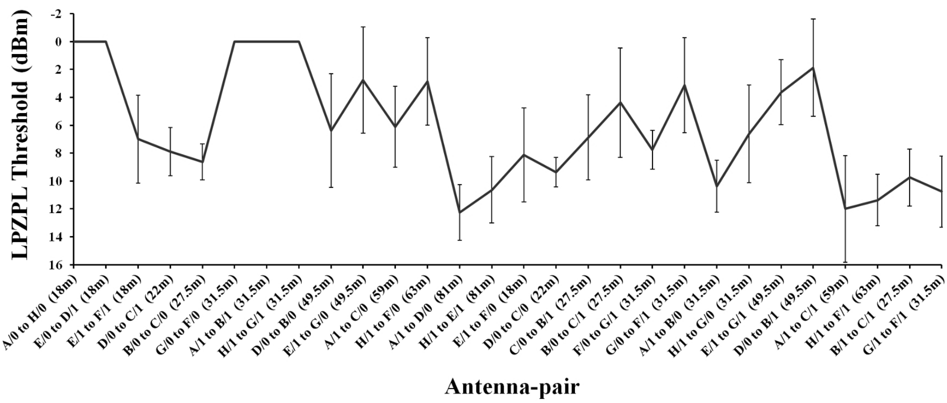


Fig. 8. The mean and standard deviation of link quality

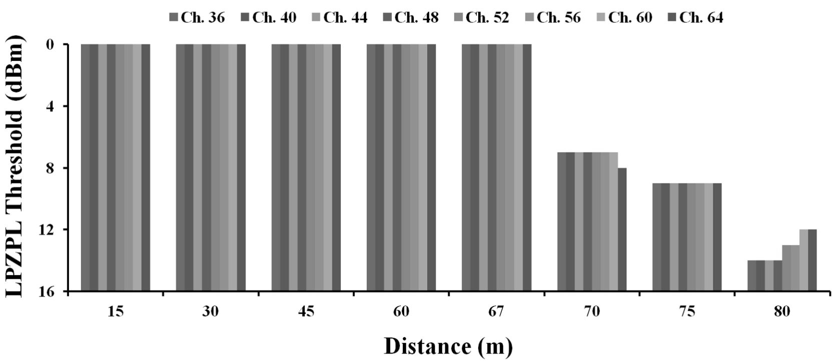


Fig. 9. Outdoor Link quality comparison across channels

ERC building (Fig. 9). The outdoor link quality value exhibits best quality until the antennae are 67m apart. It also shows a consistency across lower 8 channels, even when the quality starts to degrade with increasing distance.

4.3 Discussion and Analysis

In this section, we go through our main observations so as to expand on the implication of each.

***Uniformity of link performance over all channels in IEEE 802.11a**:* As mentioned before, the link quality over upper 4 channels (U-NII upper band) of the IEEE 802.11a standard is significantly worse than over the lower 8 channels (U-NII lower and middle bands). In fact, most antenna-pairs experienced packet loss at the maximum TxPower at one or more upper band channels. The consequence of this is that, even though all 12 channels in U-NII bands are stipulated to be used indoors, only a portion of 8 channels are capable of providing acceptable levels of link quality. Thus, a channel selection scheme that randomly selects a channel to be used between an antenna-pair, in an indoor mesh network, has a 1 in 3 chance of picking a channel with an inferior performance.

However, a more thorough perusal of the results provides a deterrent to this simplified conclusion. That is, while the link quality results of many antenna-pairs falls within this generalized supposition, there are some, albeit a very few, antenna-pairs that showcase similar link quality values across all 12 channels. For example, between antenna 0 of MR B and antenna 1 of MR C, the link quality over all the upper band channels is at 10 dBm, the same as it is at channel 36 and not far above the 3--8 dBm range across the rest of the lower channels. A similar trend is evident between the antennae 0 of MR B and C.

Clearly, this indicates three important realities:

- The simplistic assumption of uniform performance across all the orthogonal channels in IEEE 802.11a is not totally accurate for an indoor environment.
- There is a marked difference between the indoor link quality of an antenna-pair using one of the lower 8 channels (36--64) or one of the upper 4 channels (149--161).
- Even when there is a clear distinction between the performance of different channels, or certain groups of channels based on a given criteria, we can make the most accurate decisions only by comparing individual link quality across all the channels.

Uniformity of link performance over lower 8 channels in IEEE 802.11a: Having observed enhanced performance of lower 8 channels in providing better link quality between an indoor antenna-pair, we were interested to see whether the assumption of uniform performance holds at least across those channels.

From the evidence of Fig. 7 and Fig. 8, apart from few antenna-pairs (5 out of 28, A/0 and H/0, E/0 and D/1, G/0 and F/0, A/1 and B/1, and G/1 and H/1, to be precise), the link quality across the lower 8 channels cannot be assumed to be uniform. If we focus our attention on the 23 antenna-pairs having inconsistent link quality across the channels in Fig. 7, 12 out of those 23 antenna-pairs have the best link quality (LPZPL threshold at 0dBm) over some of the channels, while the link quality over the rest of the channels are varied, even on the poor side. This is typified by the moderate to high variability shown by the link quality values of all these 23 antenna-pairs, as indicated by Fig. 8. On the other hand, link quality values are consistent across the lower 8 channels in an outdoor environment, even when the values are below the average as seen in Fig. 9.

Interestingly, the best to worst performing channels for each link is different as well. For example, the antenna-pairs E/1 and F/1, E/1 and F/0, C/0 and B/1, and H/1 and G/0 have the best link quality at channels 60, 64, 52 and 40 respectively. The range of link quality over the rest of the channels are 6-11, 8-10, 6-10 and 4-11 respectively. Thus, we can conclude the following for an indoor network:

- The link quality across the lower 8 channels of IEEE 802.11a cannot be assumed to be uniform.
- The best to worst performing channels for links in the same neighborhood varies considerably.

Predictability of link performance: Once it was obvious that the link performance across all, and even the lower 8 channels, are not uniform, our focus turned towards predicting the link performance based on some good criteria. Intuitively, the links in the *facing-facing* category should perform better then the links in the *facing-opposing* category which in turn should do better than the *opposing-opposing* category. Intuitively, the link performance should also decrease as the distance between the antenna-pair increases. With this in mind we first sorted the data based on the categories of relative orientation and then based on relative distance (Fig. 7).

The data in Fig. 7 provides us with some interesting observations. We have already seen that the assumption of uniform performance across the lower channels does not hold true, except in a few specific circumstances. However, generalizing these circumstances based on relative orientation and distance is not viable, as evident from the top 8 antenna-pairs in Fig. 7. Interestingly, while 3 antenna-pairs facing each other with distances between 18m—27.5m, exhibit poor link quality results, antenna-pairs in *facing—opposing* category with distance of 49.5m performs nearly the best. This inexplicable contrast between the link quality of the two sets of antenna-pairs can only be attributed to the influence of the building design.

Then again, one could argue that those antenna-pairs with inferior quality are due to defective hardware. However, careful observation of Fig. 7 reveals that every single antenna has at least two channels at which it exhibits the best link quality with another antenna.

Another peculiar observation is the improvement in the link quality with increasing distance in the *facing—opposing* category (Fig. 7 and Fig. 8). In fact, most *facing—opposing* antenna-pairs have higher best link quality channels than some of the *facing—facing* antenna-pairs. However, by far, the most interesting observation is the link quality values of *facing—facing* and *opposing—opposing* antenna-pairs of the MRs in the middle of each corridor shown in Fig. 10. While one of the *facing—facing* antenna-pairs (F/0 and G/0) exhibit best link quality across all the channels, the other *facing—facing* antenna-pairs link quality values are almost similar to that of *opposing—opposing* antenna-pairs.

Of course, changes in the relative locations of the beams and the columns would affect the waveguide properties of the corridor between antennae [19, 20, 34]. However, if that, or any other property in the building design, influences the link quality between an antenna-pair over different channels, then, unquestionably, predicting the performance is a futile exercise. Therefore, we can conclude that:

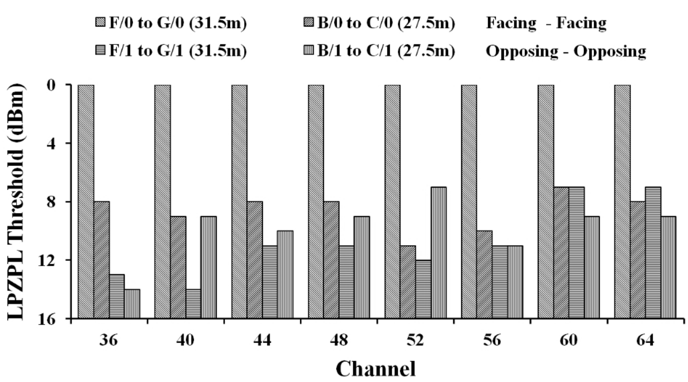


Fig. 10. Example Case: Comparison of link quality values for antenna-pair combinations facing-facing and opposing-opposing of MRs in the middle of the corridor

- The inexplicable and unpredictable impact of the building design makes it impossible to generalize the link quality between an antenna-pair based on any criteria.
- We would be best served by having a-priori knowledge of the link quality between each antenna-pair over all the channels.

4.4 Summary

In summarizing the results and their implications, it is important to remember that our MRs are equipped with directional patch antennae, which have enhanced communication capability in one direction. Thus, we started by analyzing the antenna-pairs that are facing each other, expecting the best possible link quality across all channels. On the contrary, we found that not only this is untrue, but also, the link quality between such an antenna-pair across different channels is not predictable. We also observed that when the antenna-pair is *facing-opposing*, the link quality statistics are comparable to the *facing-facing* category. That is, in addition to having best possible link quality at some instances between some antenna-pairs, the link quality data also showcase the traits of high variability and unpredictability.

We went even further and analyzed the link quality between antennae where one or both are oriented in a perpendicular direction to the other. Even though these antenna-pairs display the most inferior link quality results as a group, there are certain antenna-pairs that exhibit better link quality than even some of the antenna-pairs that are facing each other.

These observations are critical as when designing a multi-channel multi-radio mesh network, it is not possible to always have two antennae belonging to two MRs facing each other. Even when they do, forcing the channel selection to favor antennae facing each other not only puts a strain on all the other criteria that comes into the picture [3], but also does not offer any definite advantage based on the detailed observations presented here. Rather, relying on individual link quality data of each antenna-pair over all the channels would provide a higher degree of freedom, in addition to better performance.

5. AUTOMATED LINK QUALITY

The previous sections indicate that prior knowledge of link quality can be useful during the channel selection phase of a WMN. However, incorporating the manual collection of this data into a dynamic and an automated process of WMN configuration is impractical. This motivates the need for an automated process to measure the link quality of every link across all channels. Our experience while manually collecting the first set of data, helped create an automated rule-based script that matched the results of the manual data collection. We identified two main challenges while creating the automated program. The first was due to the beacon synchronization and IBSS (ad hoc mode) merging problem that exist in ad hoc mode implementations in wireless drivers [31]. The second was due to inconsistencies in the wireless device drivers of the mesh router. Once the problems were isolated, we found workarounds to detect and avoid these pitfalls and decrease the incidence of IBSS merge failures, which we incorporated into our automated program.

Manually gathered link quality data exhibits trends that are identical to the ones presented in the previous section, which were based on combined results. This was expected, as during the manual data gathering phase we could detect anomalies and repeat the measurements, reducing

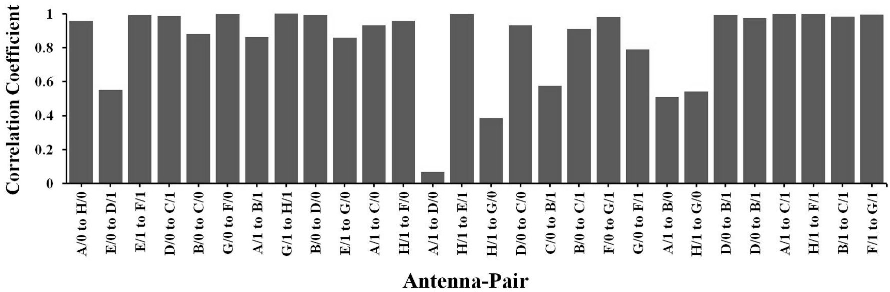


Fig. 11. Correlation Coefficients

the chances of having any result other than the most accurate link quality for each antenna-pair across all channels. On the other hand, since the automated program is employing a rule-based script to trigger IBSS merges and obtain accurate link quality data, it is imperative that we establish the validity of the data.

To measure the quality of the automated script, we calculated the correlation coefficient between overall and automated results for each antenna-pair (Fig. 11). The mean of the correlation coefficient is **0.84**, indicating that the results from the automated script matches up to the overall results well. Additionally, if we disregard the five lowest coefficient values, the mean jumps up to **0.94**. Above all, this demonstrates that the automated program is capable of gathering link quality data that matches with manually gathered data, in most situations. Interestingly, when it fails, in almost all those instances, it is due to IBSS merge failure, signified by the 100% packet loss

Apart from the few cases where the IBSS merge fails, the variability between the data gathered by the manual and automated processes is quite low. This signifies two things:

- The automated process has largely corroborated the data gathered by the manual process, and
- The data gathered by the manual process are indeed repeatable.

Now, the only question that remains is about the instances where the automated process is unable to trigger an IBSS merge between certain antenna-pairs, thereby not being able to gather the real link quality for those pairs. However, we observe that if an IBSS merge between a certain antenna-pair is not achievable by the logic employed in the automated program, then that link is of no use to the WMN, whatever the real link quality between that antenna-pair. Whenever the logic used to trigger IBSS merges fails for a certain antenna-pair, its impact is common to the automated process that is used to gather link quality data, as well as the process that is used to configure the WMN. This makes the former the ideal companion to gather the a-priori knowledge that will be used by the latter in configuring a WMN.

In summary, we have established the following facts about the automated process that is used to gather link quality data.

- Firstly, the results gathered by the manual process are matched by the automated process, except in rare cases when it fails to trigger IBSS merges between antenna-pairs. That is, the accuracy of the automated process is more than satisfactory.

- Secondly, whenever the logic that is used to trigger IBSS merges fail for a certain antenna-pair, its impact is common to the automated process that is used to gather link quality data, as well as, the process that is used to configure a WMN. This makes the former the ideal companion to gather the priori knowledge that will be used by the latter in configuring a WMN with best performance.

6. CONCLUSION

In this paper, we presented a measurement-driven study to compare the link quality of different channels in an IEEE 802.11a based indoor WMN. In essence, our study shows that the performance of links in our WMN test bed across the 12 orthogonal channels in IEEE 802.11a is not consistent enough to be assumed uniform. The main observations of our study, which have been done in an interference free environment, are as follows:

- In IEEE 802.11a, the link performance over the 4 channels in U-NII upper band is significantly worse than the 8 channels in U-NII lower and middle bands in an indoor environment.
- Even when only the lower 8 channels are considered, there are still variations in the link quality over different channels for a given link. In fact, we found that depending upon relative position and orientation of the antennae, the link quality displays zero to high variability across the channels in the IEEE 802.11a standard.
- A channel that works best for a given link could be the worst for another link in the same neighborhood and vice versa. This factor is affected by the distance between the antennae, its relative orientation and the surrounding building structure.

The main implication of our finding is that we are forced to reduce the number of orthogonal channels effectively available for many links and makes it hard to predict the link quality without actually measuring it first. Similar results have been reported in [35].

While analyzing this data, it is important to remember that we conducted our tests at night to minimize the interference, and also used repetition to find the best possible link quality devoid of any interference. Consequently, as interference has been shown to have the most effect on the performance of wireless networks [25], these link quality values could only get worse in a fully operational multi-radio multichannel wireless mesh network. With the rise of multimedia and networking technologies, the inability of links to handle the bandwidth requirement of data could cause network congestions that would lead to delays and packet losses [36]. Thus, the importance of using per channel link quality data in the initial design on a WMN, to address the joint problem of routing and channel assignment, cannot be overestimated. The information provided by a link quality metric such as LPZPL could be used to design a network with precise transmission power values to limit the interference and maximizing the performance.

However, as there are many degrees of freedom in designing a WMN (e.g., chipset, antennae, number of radios, antennae location, etc.) and as the respective environments are always unique, it is important that we analyze a result like ours with the big picture in mind. While we took a painstaking effort to fine-tune our test bed for the best performance across major links (e.g., placement, orientation of antennae, antenna separation, etc.), we recognize that a WMN could be built for better (e.g., through thorough and complex radio engineering) or for worse performance [37].

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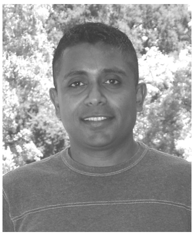

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