

A Guide to Channel Assignment and Antenna Placement in IEEE 802.11 Based Multi-channel Multi-radio Wireless Networks

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Abstract— The use of multiple radios tuned to non-overlapped channels, can increase the throughput of a wireless network. However, equipping a node with multiple radios can cause a proximity problem between antennas. In this context, the leakage power generated from co-located antennas, which is known as inter-radio interference (or inter-antenna interference), causes throughput degradation. In order to prevent this throughput degradation, we have to consider the inter-radio interference in the assignment of channels to each radio and when designing the placement of the antenna at a node. In this paper, we verified the existence of inter-radio interference and its impact on the throughput via testbed experiments. We also investigated the change of the inter-radio interference given various channel separation and antenna distance combinations on a node. Furthermore, we put more emphasis on finding the relationship between the channel separation and antenna distance in terms of the inter-radio interference. Based on our findings, we present a useful guide to assigning channels and to designing antenna placement at a node.

Keywords— Adjacent channel interference, Multi-radio multi-channel wireless networks, Inter-radio interference, Channel assignment, Antenna placement

I. INTRODUCTION

Today, with explosive growth in the use of the mobile Internet, the rapid establishment of a broadband wireless access network has become more important. Hence, wireless mesh networks (WMNs) have received more attention in the wireless community as a type of broadband wireless access network [15]-[17], as wireless mesh networks can build wireless access networks rapidly and inexpensively by replacing legacy-wired links between access points (APs) with wireless links. The elimination of wiring, which is the main cost of network installation and maintenance, enables WMNs to be a serious contender in the competition among the alternatives to broadband wireless access networks. While WMNs have the considerable advantage of being able to extend a wireless access network cost-effectively, the possibility exists of having much lower throughput than a typical Wi-Fi network operating in the infrastructure mode. This throughput problem is mainly due to the use of single

channel over a network, despite the fact that the IEEE 802.11 standard provides 3 and 12 non-overlapping channels for 11b/g, and 11a respectively. Due to the half-duplex nature of the wireless medium, there is only one link activated among successive links with a same channel. If a node adopts multiple radios tuned to non-overlapped channels, the network throughput increases significantly due to the allowance of parallel transmissions. This occurs because assigning a different channel to each radio has the effect of dividing one large collision domain into multiple small collision domains. It reduces the number of contending nodes in a collision domain.

However, if we adopt multiple radios on a node, we face the new limitation of interference among co-located radios on a node. With IEEE 802.11 commodity hardware devices, a device uses one antenna for both transmission and reception. As a result, a mapping between radios and antennas is one-to-one; thus, a device operates in only the TDD (time-division duplexing) mode.

Therefore, the number of antennas on a node increases as we add radios to the node (radio and antenna can therefore be used interchangeably in this paper). As a result, equipping a node with multiple radios results in close proximity between antennas. In this context, the inter-radio interference, which is leakage power generated from co-located antennas, is the main limiting factor associated with network throughput.

Despite the considerable body of research that aims to reveal the effect of the inter-radio interference, most studies have focused either solely on the antenna distance or on channel separation.

Therefore, in this paper, we investigate the change in the inter-radio interference on the various channel separation and antenna distance combinations on a node. Furthermore, we put more emphasis on finding the relationship between channel separation and antenna distance in the inter-radio interference. Based on this finding, we present a useful guide to assigning channels and to designing antenna placement at a node.

To the best of our knowledge, this work is the first comprehensive measurement study to reveal the relationship between channel separation and antenna distance and to

quantify this relationship to reduce inter-radio interference to an acceptable level (as detailed in section V.C).

The rest of the paper is organized as follows. In section II we discuss related work, and section III provides the details of experimental testbed. Section IV presents the baseline experiment, and section V shows the effect of inter-radio interference on various transmission configurations. We present the result and analysis of the throughput degradation and inter-radio interference in sections VI and VII respectively. Finally we conclude the paper in section VIII.

II. RELATED WORK

The several studies of aiming to identify practical issues of WMNs have been done in recent years. In [1], the authors performed experiments with three nodes equipped with two 802.11b radios. They concluded that although multiple radios were installed onto a node so as to increase the capacity, a capacity gain could not in fact be obtained in this manner, as each radio could not operate independently unless they were separated by 35dB (>1m). They studied only the antenna distance to mitigate inter-radio interference. In [2], the authors noted that no two radios could operate independently on a node without throughput degradation and that the number of orthogonal channels must be determined experimentally.

Through experiments, the authors in [3] found that one radio interferes with another on a node even when their channels are set to extreme ends of the 802.11a spectrum. They suggested that the best alternative was to operate one in 802.11a mode and the other in 802.11b/g mode. In [4], the authors introduced three experiments based on the transmission configuration of the intermediate node in a linear topology. If two radios on the intermediate node receive packets at a same time, there is no throughput reduction. The results in other cases (such as both radios transmitting on the intermediate node) were similar to those of previous works. The authors in [5] found that even when the nodes use radio chipsets that satisfy the transmit-mask requirement set by the IEEE 802.11 standard, a radio transmitting on a node can interfere with its own receiving radios on different channels. Kyasanuri proposed a framework that can support multi-radio MAC system in a Linux environment, showing measurements in which 5 channels (36, 52, 64, 149, and 161) among 12 non-overlapping channels could be used simultaneously in their testbed [6]. Jing Zhu et al. presented challenges and opportunities related to the use of multiple radios on a node [7]. Unlike earlier works, the authors studied the coexistence of radios belonging to heterogeneous technologies such as Wi-Fi, WiMAX, and Zigbee. The authors also infer that the transmit-mask requirement is not intended to resolve inter-radio interference among co-located radios and is therefore not sufficient to handle the inter-radio interference. In addition, the authors stressed that while antenna isolation is a common means of increasing the degree of pathloss between radios, it has a space limitation, especially for mobile devices. Raman et al. studied the use of WLAN to establish long-distance 802.11 mesh network [8]. They adopted directional antennas to build point-to-point links. Although they equipped a node with

multiple directional antennas, there was no throughput gain due to the side lobes of directional antennas, which again generated inter-radio interference. Hence, they proposed a software solution which they referred to 2P to schedule packet transmission and reception by multiple radios on a node by allowing either synchronized transmission only or synchronized reception only. In [9], the authors introduced a Wi-Fi-array to support high throughput data transmission in mesh backhauls. This work is similar to 2P [8] in that both prohibit simultaneous reception/transmission and schedule one radio to be synchronized with the other when receiving or sending.

Prohibiting simultaneous reception/transmission on a relay node in multi-hop networks reduces the opportunities to relay data traffic. This limitation stems from the assumption that simultaneous transmission and reception on a node is impossible. However, this is not true if we set the channel separation and antenna distance appropriately.

Although all of the previous works were in agreement regarding the existence of inter-radio interference, some of the experimental results are inconsistent with others. This inconsistency is the motivation for the present study

As inter-radio interference depends on the facts of channel separation and antenna distance, both should be taken into account. However, most previous works were focused either on channel separation or antenna distance. Therefore, in our work, we determine the relationship between these two factors and present a guide based on the relationship. The guide that can be drawn from our work will assist channel assignment and antenna placement so that optimal throughput can be obtained through the use of multiple radios per node.

III. EXPERIMENTAL TESTBED

We explain the testbed for the experiments in this section. We used three Intel dual-core-based desktops running the Fedora Linux (version 12). Each node was equipped with two 3-Com wireless network interfaces based on the Atheros chipset (AR5212). The open source Madwifi driver (version 0.9.4 and ath5k) [10] was used, modified for wireless network interfaces. Auto-rate control was disabled, as was the RTS/CTS mechanism. Iperf [11] was used to generate UDP packets and to obtain the throughput results in all experiments, unless otherwise mentioned. The transmission rates were locked at 54Mbps with a transmit power of 17dBm and a UDP packet size of 1000bytes.

IV. BASELINE EXPERIMENT

First, we conducted a simple baseline experiment so as to determine the achievable throughput of the IEEE 802.11a band experimentally using commodity hardware devices. We formulated a linear topology with the two testbed nodes labeled A and B. We used the Iperf application to generate UDP traffic from node A to node B. Although the IEEE 802.11a physical layer supports 54Mbps, the achievable throughput was observed to be around 35Mbps due to the MAC overhead, including the back-off procedure, contentions, and MAC-level acknowledgements.

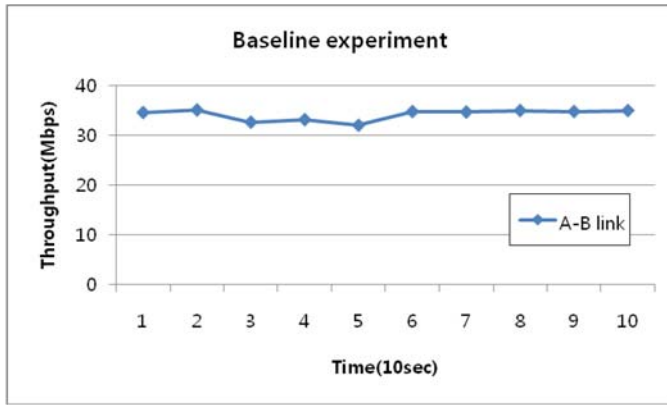


Figure 1. The achievable throughput of the IEEE 802.11a links.

V. EFFECT OF INTER-RADIO INTERFERENCE

To verify this work, we conducted two experiments that indicated the existence of inter-radio interference. We conducted two preliminary experiments using a linear topology consisting of three testbed nodes labeled A, B and C in a lab environment. We used 802.11a radios in these experiments. We measured throughput of three different configurations on relay node B

In the two experiments, we set the antenna distance to 5 inches and assigned two adjacent channels (channel 36 and 40). The distance between the testbed nodes was 7 meters.

Although the transmission configuration at relay node B differed in the two cases, the settings in experiment 1 and 2 were simply traditional two-hop, two-channel settings.

A. Experiment 1: Tx-Tx Case in Relay node B

In this experiment, one radio at node B transmits to node A on channel X, while the other transmits to node C on channel Y. Transmission occurs on both radios at relay node B.



Figure 2. The topology and configuration used in experiment 1.

B. Experiment 2: Tx-Rx Case in Relay node B

In experiment 2, Node A sends UDP packets to node C via node B. One radio at node B transmits packets to C on channel Y while the other receives packets from node A on channel X.



Figure 3. The topology and configuration used in experiment 2.

C. Results and Analysis

In Figures 4 and 5, the dotted line indicates the throughput (about 35Mbps) when using single-channel single-radio devices as in the baseline experiment. If there is no inter-radio interference, the aggregated throughput of the two links should be around 70Mbps.

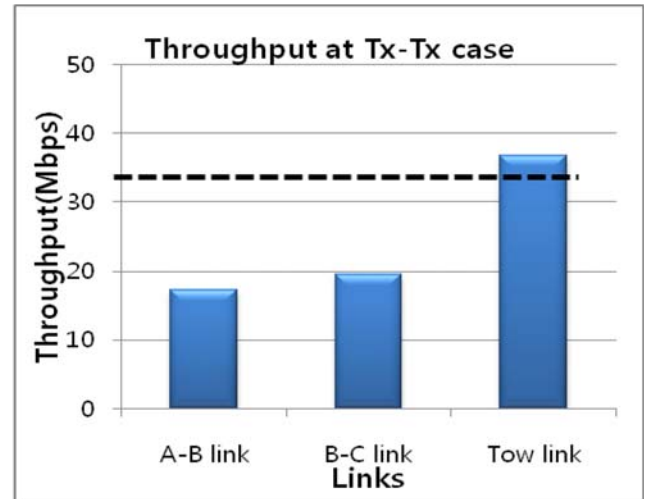


Figure 4. The throughput measurement of each link in experiment 1

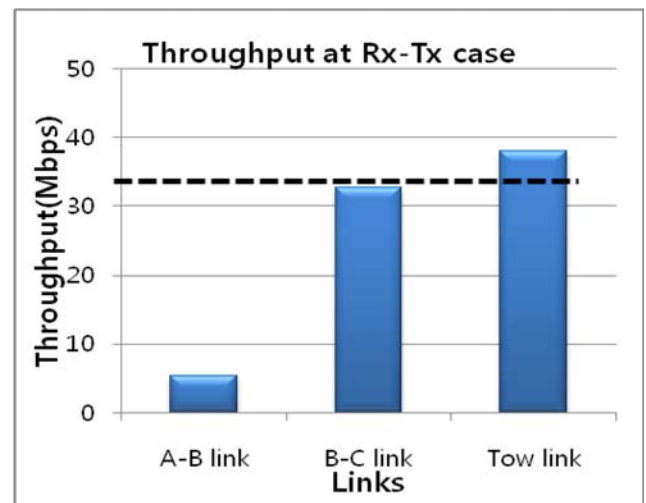


Figure 5. The throughput measurement of each link in experiment 2.

As shown in Figures 4 and 5, even when we use two radios with two different channels in a two-hop environment, we cannot obtain any throughput gain.

The results of the two experiments are similar to each other, but the reasons for the throughput reduction are wholly different in the two cases. To determine the difference, we delved into the results from two experiments with a packet analyzer, Commview Wi-Fi [12] version 5.6.

In experiment 1, we found that there is only one activated link due to the false negative error in the CCA (clear channel assessment). To obtain access to a channel, a node has to perform the CCA procedure before starting its transmission to check whether or not the medium is busy. If a node can sense the power from a channel above a certain CCA threshold (-82dBm if the preamble was decoded successfully), the node assumes that the medium is busy. A false negative of the CCA mechanism can occur because there is significant power leakage from the nearby antennas.

In experiment 2, we noted that the result that the packet error rate of the reception link, the A-B link, is much higher than that of the transmission link, the B-C link.

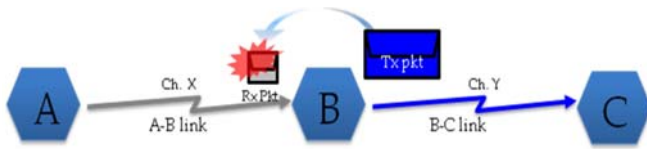


Figure 6. The packets from B-C link corrupt the packets from the A-B link.

This occurred because the SINR (Signal to Interference-plus-Noise Ratio) of the reception link does not meet the requirement, which is 23dB at 54Mbps. Figure 6 shows that the transmission link corrupts the reception link.

As a result, when both radios on a node either transmit or receive, the wireless medium is equally shared among the radios due to the CSMA/CA property. However, when one radio transmits and the other receives, the transmission link can starve the reception link. Our results indicate that even when the antennas operated on non-overlapping channels, they continue to affect each other when they are placed too closely

VI. THROUGHPUT IMPACT OF CHANNEL SEPARATION AND THE ANTENNA DISTANCE

We performed a number of two-hop throughput measurements in our laboratory. We used three nodes, labeled A, B, and C, with the intention of sending traffic from node A to node C via node B as in experiment 2 in the previous section. The goal of this section is to measure and analyze the impact of the throughput caused by the channel separation and antenna distance among radios in a node. We conducted the experiments at a channel separation of 20 and at 40MHz and with antenna distances of 0, 1, and 2 meters.

In Figures 7 and 8, the left bar indicates the throughput of the transmission link, the B-C link while the right bar indicates the throughput of the reception link, the A-B link. As shown in Figure 7, if we use two adjacent channels (channels 36 and 40), the aggregated throughput drops by half in the throughput of the baseline experiment regardless of the distance between the antennas. This problem occurs due to the imperfect filter operation of commodity Wi-Fi devices [13].

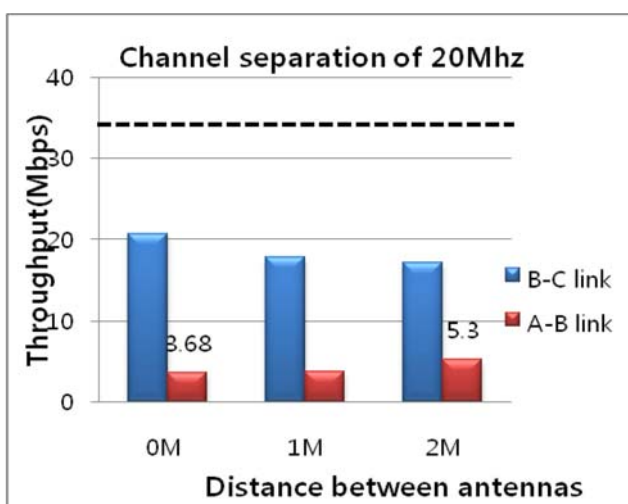


Figure 7. Link throughput at channel separation of 20Mhz.

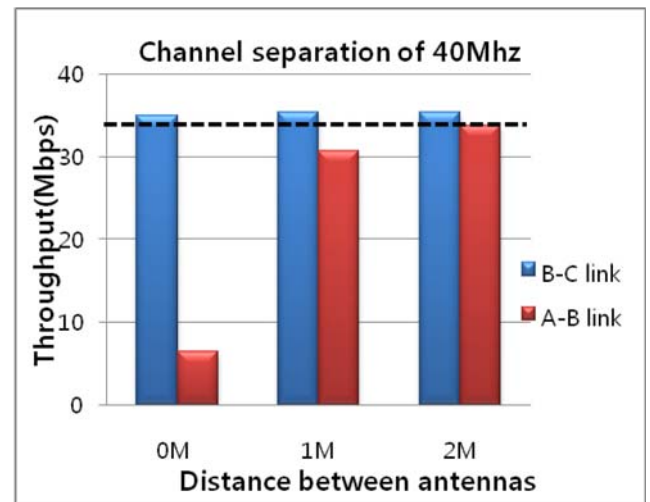


Figure 8. Link throughput at channel separation of 40Mhz.

The lesson from the previous section is that insufficient antenna separation essentially prevents a node from simultaneous transmission and reception, while offering no non-interfering communication channels. However, if we use two adjacent channels, an increase in the distance between the antennas does not help much. In addition, if the successful reception rate of the A-B link increases, the generation of acknowledgements to inform the sender node of successful reception increases. These increased acknowledgement packets interfere with the B-C link again. In Figure 7, we can confirm that if we increase the distance between the antennas, the throughput of the A-B link increases while the throughput of B-C link decreases. In contrast, in Figure 8, if we separate the channels by 40MHz, our testbed requires a distance of 1 meter between co-located antennas before one no longer affects the throughput of the other.

When antennas are separated by 1 meter or less, the throughput of the A-B link falls from 35Mbps to 6 Mbps even with channel separation of 40MHz.

This leads us to believe that transmission and reception can take place on a node if we set channel separation and antenna distance properly and that inter-radio interference is not solely dependent on either channel separation or the antenna distance.

VII. MEASUREMENT OF THE INTER-RADIO INTERFERENCE UNDER VARIOUS CONDITIONS

In this section, we measured and quantified the inter-radio interference with different antenna distance and channel separation conditions, as discussed in earlier section. Based on the measurement results, we derive the relationship between the antenna distance and channel separation, as shown in Figure 9. To measure the inter-radio interference, we used the RSSI value which is reported by the device driver when a packet is received. Atheros-based chipsets report the RSSI value in the dBm scale (The unit of the RSSI value is vendor specific). Although one advantage of using the RSSI value is that it can be read easily, the RSSI value is reported only when a packet is received. This limited reporting time is a drawback of using this measurement.

As we needed to read the RSSI value when the packets transmitted on different channels, the Madwifi driver was modified so that it would freely access the hardware register of the RSSI regardless of the packet reception.

Figure 9 shows the received signal strength with one radio continuously broadcasting UDP packets at a frequency of 5.18GHz with different antenna distances. In Figure 9, the vertical axis indicates the inter-radio interference and the distance between the antennas varies from 0 to 40 inches. Figure 9 shows the relationship between channel separation and the antenna distance as well as the solution to the problem discussed in the sections V, and VI.

A. Handling the False Negative Error of the CCA

We mentioned the false negative error of the CCA in the section V. To avoid the unnecessary backoffs due to the false negative error of the CCA, the inter-radio interference should not exceed the CCA threshold line which is located at -82dBm in Figure 9. As shown in Figure 9, there are several points that do not exceed the CCA threshold line. For example, if we set the channel separation to 40MHz, we should separate the antennas by 10 inches (the curve with triangles in Figure 9). As another example, if we have to set the distance between antennas to 5 inches owing to the space limitation of a node, we should separate the channels by 60MHz (which is the point at 5.24GHz). Unlike other previous works, we stress that there is no fixed solution, such as the use of non-adjacent channels (using channels separated by 40MHz) or placing the antennas at a distance of 1m. The solution condition should change based on parameters such as the space limitation of a node or the number of available channels in a network.

B. Handling the Packet Corruption of Reception link

To handle packet corruption on the reception link, the received signal-to-noise-plus-inter-radio-interference ratio should meet the required SINR. We draw example lines indicating the required SINR and receiver sensitivity,

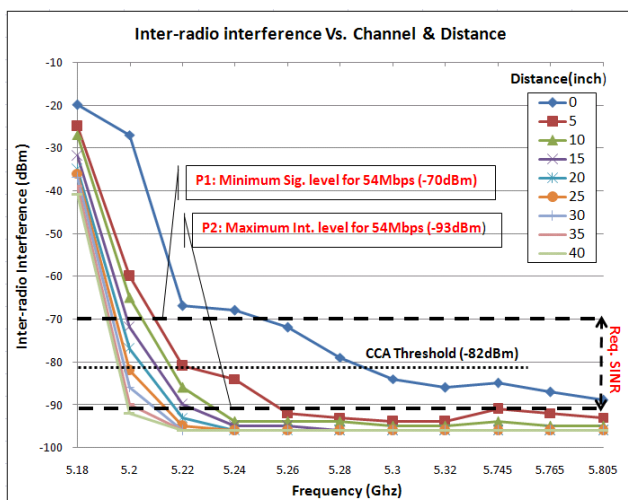


Figure 9. Inter-radio interference based on channel separation and the antenna distance.

representing the minimum requirement of the received signal to decode a packet without errors.

To support 54Mbps when a received signal is -70dBm (P1 line in Figure 9), the inter-radio interference coming from co-located antennas should be less than the P2 line, which indicates maximum inter-radio interference level for 54Mbps. It is interesting to note that if we determine the channel separation and antenna distance, the inter-radio interference is constant while the received signal varies based on factors such as the pathloss. This property indicates that if the received signal is not strong, a node experiences more inter-radio interference.

VIII. CONCLUSIONS

Unless we consider the inter-radio interference, the throughput gain when using multiple radios can be diminished: otherwise we cannot obtain any gain. Inter-radio interference is not solely dependent on either channel separation or antenna distance but is determined instead by a combination of the channel separation and antenna distance. We verified and quantified the inter-radio interference under various conditions through extensive experiments. Furthermore, we derived the relationship between the channel separation and antenna distance. The result from this work will be utilized in the development of our channel assignment scheme, which takes inter-radio interference into account. It can also serve as a useful guide for those who wish to build a multi-radio wireless network. In the future, we plan to study the effect of inter-radio interference in the IEEE 802.11n [14] context.

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