

MAC Diversity in IEEE 802.11n MIMO Networks

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Abstract—*Opportunistic Routing (OR)* is a novel routing technique for wireless mesh networks that exploits the broadcast nature of the wireless medium. OR combines frames from multiple receivers and therefore creates a form of *Spatial Diversity*, called *MAC Diversity* [1]. The gain from OR is especially high in networks where the majority of links has a high packet loss probability.

The updated IEEE 802.11n standard improves the physical layer with the ability to use multiple transmit and receive antennas, i.e. Multiple-Input and Multiple-Output (MIMO), and therefore already offers spatial diversity on the physical layer, i.e. called *Physical Diversity*, which improves the reliability of a wireless link by reducing its error rate.

In this paper we quantify the gain from MAC diversity as utilized by OR in the presence of PHY diversity as provided by a MIMO system like 802.11n. We experimented with an IEEE 802.11n indoor testbed and analyzed the nature of packet losses. Our experiment results show negligible MAC diversity gains for both interference-prone 2.4GHz and interference-free 5GHz channels when using 802.11n. This is different to the observations made with single antenna systems based on 802.11b/g [1], as well as in initial studies with 802.11n [2].

Index Terms—Opportunistic Routing, MAC Diversity, PHY Diversity, IEEE 802.11n, Testbed, Wireless Networks, Research

I. INTRODUCTION

Modern routing schemes for wireless mesh networks explicitly exploit the broadcast nature of the wireless medium. An unicast packet destined to a specific node is not only received by the intended node, but also by other one-hop neighbors. Traditional routing (also called single-path routing) treats the broadcast nature as a disadvantage, because it induces interference. *Opportunistic Routing (OR)*, also called any-path routing, is such a modern broadcast exploiting routing scheme. It dynamically selects from multiple network routes [3] and therefore improves link reliability and overall system throughput. OR creates *Spatial Diversity (SD)* on the MAC layer by combining frames from multiple receivers. This diversity from selecting one out of multiple receivers is also called *MAC Diversity (MD)*. Examples of OR protocols are MRD [1], ExOR [4], McExOR [5] and MORE [6]. In the past, OR was evaluated in wireless mesh networks with single antenna nodes, i.e. Single-Input Single-Output (SISO), mainly based on the outdated 802.11a/b/g standards [4], [6]. By using an OR protocol like MORE the throughput can be doubled compared to state-of-the-art best path routing protocol [6].

To benefit from MAC diversity two conditions must be met. First, the majority of operational links must have a high

packet loss probability. Second, packet losses among different receivers must be independent or highly uncorrelated.

The updated IEEE 802.11n [7] standard promises faster networks with an increased WiFi coverage. The most important improvement on the PHY layer is the ability to receive and/or transmit simultaneously on multiple antennas (MIMO). The improvements from multiple antennas are two-fold. First, using multiple antennas at the receiver and transmitter side offers a *Spatial Diversity (SD)* gain, also called PHY diversity, which improves the reliability of a wireless link by reducing its error rate. Second, instead of SD MIMO channels can be used to simultaneously transmit multiple data streams through different antennas. This *Spatial Multiplexing (SM)* technique significantly increases the maximum data rate linearly with the number of antennas.

An open research question is the combined use of OR and MIMO systems like 802.11n. Spatial diversity obtained at the PHY layer diminishes the adverse effects of signal fading. However, due to the small spacing between antennas, shadowing based channel variations cannot be eliminated. Furthermore, it is hard to combat signal corruption due to interference, e.g. hidden-nodes are common in wireless mesh networks. On the other side, both problems (shadowing and interference) can be eliminated by exploiting macro diversity which is achieved by OR, because the nodes are well spatially separated. Thus current OR research tries to quantify the MAC diversity gain offered by OR in the presence of PHY diversity created by MIMO systems like 802.11n [2].

In this paper, we measure and analyze packet losses from an 802.11n MIMO-based indoor network and determine possible MAC diversity gain as offered by OR based on the characteristics of the analyzed MIMO links. A negative result makes any further OR research on top of MIMO systems like 802.11n less promising. Note, that our objective is not to improve any existing OR protocols.

The paper is organized as follows. In Section II, the most important related work is presented. Thereafter in Section III we explain how much gain can be expected from OR and what factors have an impact. Next, in Section IV we present experiment results from an 802.11n MIMO based indoor testbed. The results are analyzed and discussed. We close the paper with conclusions and further work.

II. RELATED WORK

Shrivastava et al. [2] analyzed the statistical dependence of packet losses in 802.11n receivers in a small indoor testbed. Their experimental setup was different. First, they

used different hardware, i.e. Edimax (EW-7728In) 802.11n (Draft 2.0) with Ralink chipset. Secondly, they analyzed only the Rf polluted 2.4GHz band where even at night the channel utilization can be significantly high (e.g. 802.11 beacons frames) and cause interference. Thirdly, they only analyzed a single 802.11n PHY mode, i.e. Spatial Multiplexing (SM) with channel bonding (300Mbps). Note, that in this mode MIMO is used to achieve SM and not SD which was incorrectly assumed by the authors. Furthermore, the used 40MHz channel is very vulnerable to interference when used in the 2.4GHz band. Fourthly, the two receivers representing the OR candidate set were spatially co-located with each other. The reported packet delivery ratios for both the 802.11n receivers were almost the same for almost all the locations ranging from 9% to 80%. Although similar loss rates were observed across both the receivers, the losses were actually independent leading to improvements in throughput due to MAC-diversity. The reported throughput gains achieved with MD vary from 12% to as high as 103%. This is different to our observations.

III. UNDERSTANDING THE GAIN FROM OR

In this section, we explain how much gain can be expected from MAC Diversity (MD) as utilized by OR and what environmental factors have an impact. Note, that the performance gain of OR protocols compared to traditional single-path routing is not exclusively based on MAC diversity and is also related to other aspects. For example, a significant gain of OR protocols comes from Multi-Path Diversity (MPD): the packets of the same flow are routed through multiple paths. This increases the spatial reuse and allows more concurrent transmissions. Furthermore, the use of MPD combined with a MAC protocol like 802.11 results in a medium contention gain. With MPD the probability to access the medium is higher. We focus on the gain from OR achieved through MD only.

In OR, a single transmitter transmits packets to a candidate relay set. For an OR transmission to be successful it is sufficient that at least one candidate is able to receive the packet (anycast). Therefore, the concept of a virtual link representing the communication link of an OR transmission was introduced. With OR, the packet reception is improved, i.e. the packet delivery ratio (PDR) of the virtual link is higher than the PDR of the particular links. Fig. 1 (top) shows the impact of the size of candidate relay sets (N) on the PDR of the corresponding virtual link.

Fig. 1 (middle) shows the direct gain from MD as a contour plot. We can observe that the advantage from MD is highest for weak links (low PDR) and for large N (large number of candidates). The gain from MD is low if the PDR of particular links is already high. Thus, in a network with high PDR links, the expected gain from MD is small. Note, that from a practical point of view due to OR coordination overhead, the size of the candidate set is mostly restricted (typically 3-5 nodes), and thus very weak links ($\text{PDR} \leq 0.1$) cannot be used [4].

A large number of links with weak PDRs is not a sufficient criterion to benefit from MD. It also depends on independent (or at least highly uncorrelated) packet losses at different

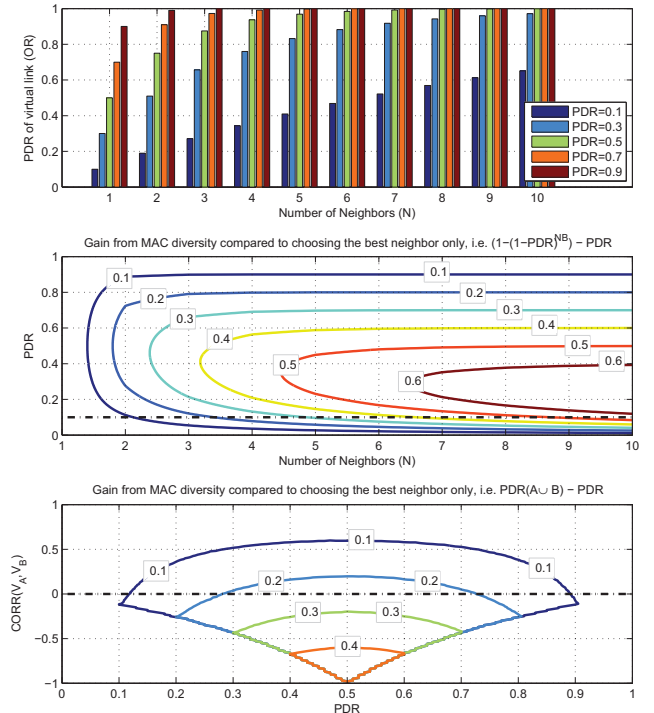


Fig. 1. Impact factors on the performance of MAC Diversity: (i) PDR to neighbor nodes, (ii) number of neighbor nodes grouped into candidate set, (iii) correlation of packet losses among different neighbors.

receivers. There is no gain from MD for two receivers with dependent packet losses, i.e. a packet is either received by both receivers or no receiver. So far we have assumed packet loss at different receivers to be independent. Fig. 1 (bottom) shows the impact of correlation for two receivers as a contour plot. The correlation, $\text{CORR}(V_A, V_B)$, is calculated from bit vectors, where each bit represents whether a packet was received or not. The result indicates that for a fully uncorrelated receiver pair with a PDR of 0.5, the gain from MD is 0.25 (the PDR of the virtual link is 0.75). However, even with a moderate correlation of 0.2 the gain from MD drops below 0.2 (the PDR of the virtual link is 0.7). With a correlation of 0.6 the gain from MD is less than 0.1. Note, that the gain from MD is highest for a negative correlation coefficient, i.e. the probability of packet reception at one receiver is higher when the packet was not successfully received by the other receiver. For two receivers with a PDR of 0.5 each and a correlation coefficient of -1, the PDR of the resulting virtual link is 1.

Which environmental factors cause correlated packet losses? Imagine two receivers that are influenced by a single hidden node (Fig. 2, top). Every time when the hidden node transmits, it corrupts the packet reception for both receivers. In this case, the correlation coefficient is 1. Now imagine two receivers that are influenced by two hidden nodes (Fig. 2, bottom). Further imagine that these hidden nodes sense each other and therefore send alternately. Hence, each hidden node only corrupts one receiver. The result is a correlation with a negative coefficient. In this example, each time one of the receivers correctly receives a packet, the other receiver fails. The correlation coefficient is -1.

From the practical viewpoint correlation coefficients of $\rho \geq 0$ are more common. To benefit from MD, an OR transmission must have a highly uncorrelated set of relay candidates.

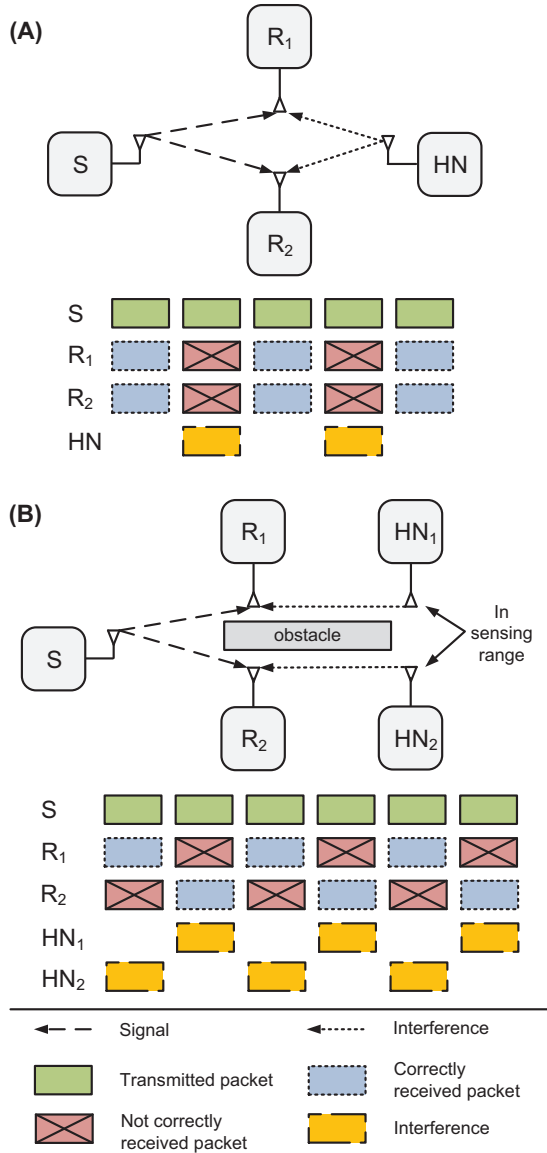


Fig. 2. Illustrative examples for correlated packet losses: (A) $\rho_{R_1, R_2} = 1$ (B) $\rho_{R_1, R_2} = -1$.

We were able to find a setup in our testbed to reproduce both scenarios and to validate our considerations. The results were left out due to space limitations.

IV. EVALUATION

The goal of this section is to evaluate the nature of packet losses in MIMO 802.11n networks. There are two reasons for packet loss in wireless mesh networks: (i) weak signals and (ii) interference [8]. Since we can control interference, i.e. by utilizing an unused channel, we are able to analyze both weak signal and interference based packet losses separately.

Moreover, we will study the effect of the used 802.11n MIMO mode; i.e. *Spatial Diversity* ($MCSIdx \leq 7$) vs. *Spatial Multiplexing* ($MCSIdx \geq 8$).

The rest of this section is structured as follows. At first we present the used experimental methodology like the used 802.11 hardware, the experimental setup and the scenarios to be studied. Thereafter, the experimental results are presented. The implications are discussed in the last section.

A. Experimental Methodology

All experiments were conducted in our 802.11n indoor testbed [9]. The nodes were placed indoors, spanning multiple buildings and floors, as depicted in Fig. 3. The network has the following characteristics: 20% of node pairs have a Euclidean distance of less than 10m to each other whereas 10% are separated by more than 45m. The median inter-node distance is 22.5m.

Wireless Node: The experiment network consists of 46 Netgear WNDR3700 routers. The WNDR3700 is an off-the-shelf wireless router with an Atheros MIPS CPU, running at 680MHz, and 64MB of RAM. It has two 802.11n radios; each radio has 4 internal metamaterial antennas from Rayspan¹. The first radio is a dual-band (Atheros AR9220) that can operate in both the 2.4 and the 5GHz band. The second radio can only be used in the 2.4GHz band (Atheros AR9223). Both radios support 2x2 SM-MIMO channel bonding and can use the short guard OFDM interval (SGI). Both WiFi chips also support Space-Time Block Code (STBC) to achieve a transmit diversity gain. The optional transmit beamforming is not supported. As driver, we used the open source ath9k developed by the linux-wireless project². For more information on our testbed refer to our paper [9].

Experiment: We performed broadcast experiments. Each experiment consists of a sequence of rounds and in each round only one of the 46 nodes is transmitting and all others act only as receivers. This ensures that the results are not influenced by internal interference. The nodes transmit MAC broadcast packets at a low packet rate to avoid problems like network saturation. The different Modulation and Coding Schemes (MCS) and channel widths (20 and 40MHz) were used in a round robin fashion.

In each round, for each MCS and packet size combination a total of 5,000 packets were transmitted in MAC broadcast mode and the receivers captured the packets using the 802.11 monitor mode. We performed 46 rounds so that each node was able to transmit exclusively. We used the receiver's captured packet traces to analyze the nature of packet losses.³

Scenarios: We want to understand the nature of packet losses in 802.11n. Especially, we want to determine the environmental factors that influence packet loss. Therefore, we performed three experiments for three different scenarios:

- 1) an occupied (busy) channel from the 2.4GHz ISM band

¹see <http://www.commnexus.org/assets/011/9474.pdf>

²<http://linuxwireless.org>

³All experimental results are available as PCAP dump files: <http://hwl.huberlin.de/uploads/measurement/or80211n/>

- 2) an unused channel from the 5 GHz ISM band
- 3) an unused channel from the 5 GHz ISM band with artificially induced interference

The focus of the first scenario is to analyze packet losses caused by weak signals or (external) interference. Therefore, we selected channel 6 (2437 MHz). This channel is used by our campus 802.11 network for serving student's internet traffic. The channel is very busy and even in the night, a significant number of 802.11 beacon frames was observed. Preceding our experiments with that channel, we measured the channel load at each node for 1 hour.⁴ The results of this measurement are shown in Fig. 4. We can see that the channel load depends heavily on the spatial location of the node, i.e. it can range from as low as 0 to as high as 31%, with a median of 4%.

For the second scenario we aimed to analyze packet losses caused by weak signals only. We selected an unused channel, i.e. channel 161 (5805 MHz). The public use of this channel is prohibited by German regulations. Preceding measurements of channel load showed zero load at all times. We therefore assume no impact from external interference (Fig. 4).

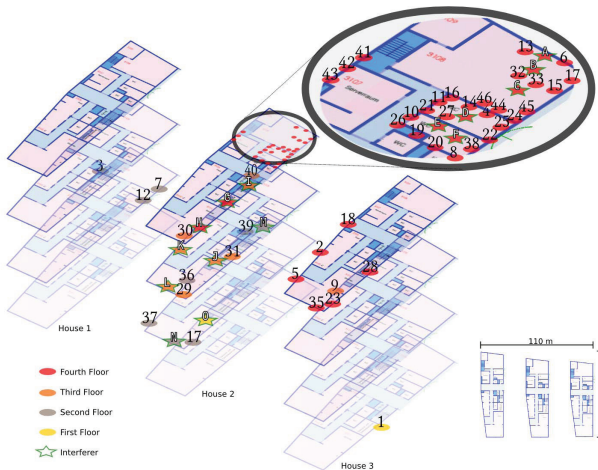


Fig. 3. Testbed topology - 46 nodes (1-46) were distributed indoors among 3 buildings on 4 floors. Furthermore, the location of the 15 interferer nodes (A-O) used in scenario 3 is shown.

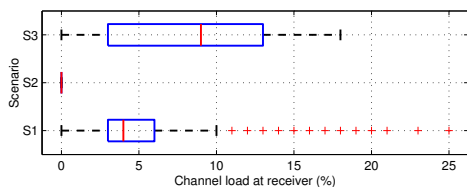


Fig. 4. Channel load as measured at each node before experiment execution.

Finally, the third scenario is different from the first scenario: we induced interference ourselves to control the amount of interference. We selected the empty channel 161 again. This time, 15 additional interferer nodes (A-O) were placed as

⁴The channel load was measured using the hardware registers of the Atheros 802.11n chip.

illustrated in Fig. 3. Each interferer (802.11abg, Atheros AR5213A) was sending broadcast packets of size 150 Bytes at a rate of 200 Hz using a PHY bitrate of 6 Mbps (802.11a). Thus, each interferer created a channel load of 4%. Note, that carrier sensing was activated. From Fig. 4, we can learn that similar to channel 6, the channel load is unevenly distributed among the nodes. The objective is to emulate the external interference from channel 6.

Parameters: The following MCS combinations were evaluated: 6 Mbps (QPSK1/2, 802.11g/a), MCSIdx=0 (QPSK1/2, 1 spatial stream), MCSIdx=7 (64QAM5/6, 1 spatial stream), MCSIdx=8 (QPSK1/2, 2 spatial streams) and MCSIdx=15 (64QAM5/6, 2 spatial streams). Note, that for all MCS combinations with an index larger 7 spatial multiplexing is used instead of SD, i.e. no spatial diversity is utilized at the PHY layer. Furthermore, the channel width was varied between 20 and 40 MHz, an OFDM Long Guard Interval (LGI), and packet sizes of 2200 Bytes and 100 Bytes were used.

B. Results

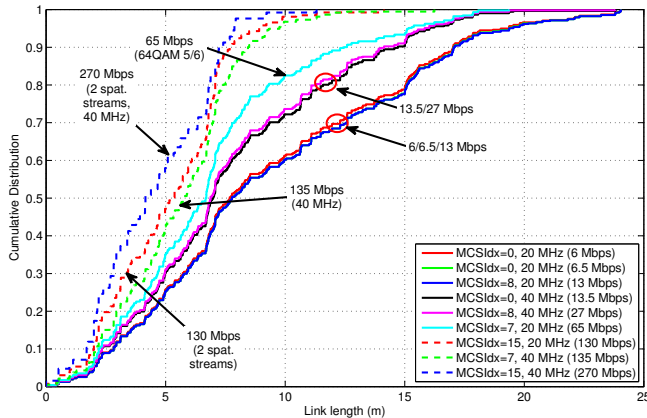
1) *Link length:* Before we present the actual experiment results, we need to understand the potential impact of the chosen scenario on packet losses. We start with an analysis of link length distribution (Fig. 5). In our model a link between two nodes exists when the packet error rate is below 90%.

If compared to channel 161 (in scenario 2 and 3), links are shorter on channel 6 (scenario 1). With the lowest MCS (i.e. 6 or 6.5 Mbps) only 10% of the channel 6 links are longer than 17 m, compared to 20 m for channel 161 links. If we use the highest MCS the difference is even higher, i.e. the maximum link lengths are around 7.2 m and 10.6 m respectively.

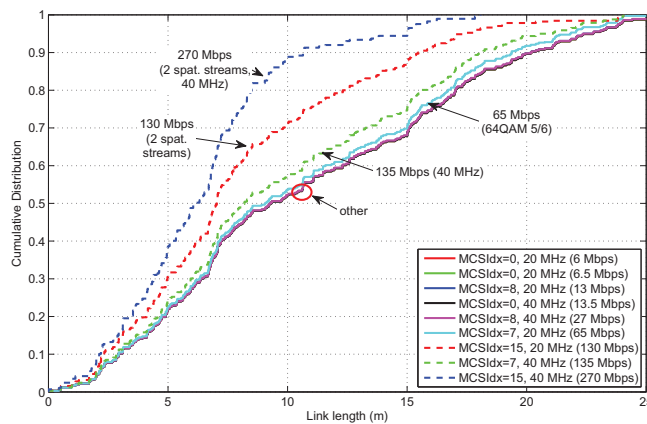
The short communication range, especially at high MCSs, was one reason for us to place a significant number of nodes very close to each other (ref. to house 2, fourth floor, Fig. 3). A 5 GHz channel on the other hand has the potential for longer links due to higher transmission power [9]. To accustom potentially longer links on channel 161, we also placed a few nodes at longer distances. On both channels, links are shorter when using a higher MCS.

We cannot observe any link length differences on channel 6 between 13.5 and 27 Mbps, and between 6, 6.5, and 13 Mbps. Finally, we cannot see any difference between 802.11n and the outdated 802.11g/a, if we use the lowest MCS (cmp. 6.5 Mbps vs. 6 Mbps). The improved STBC based diversity in 802.11n did not result in a notable increased communication range. Note, that the manually induced interference on channel 161 (scenario 3) had no impact on the distribution of the link length.

2) *Link Packet Delivery Ratio:* In a next step, we look at packet loss. We calculated the *Packet Delivery Ratio* (PDR) for each link and each evaluated PHY mode, i.e. MCS, MIMO mode (SD vs. SM), and channel width (20 vs. 40 MHz) combination. Notice, MAC diversity gains are higher for environments where the majority of links have weak or intermediate PDRs. The gain from MD is low or nonexistent if the majority of links have a high PDR, i.e.



(a) Scenario 1 (channel 6)



(b) Scenario 2/3 (channel 161)

Fig. 5. Link length distribution.

≥ 0.9 . Since MD is some kind of selection diversity it can only improve the PDR of the virtual link. From the practical point of view, links with too small PDRs, i.e. ≤ 0.1 cannot be utilized [4]. The required coordination between candidates of an OR transmission induce a significant management overhead which can exceed the achieved MD gain. For the following, we qualify all PDRs between 0.1 and 0.9 as intermediate.

Fig. 6 shows the distribution of link PDRs for all three scenarios. In scenario 1 (channel 6), 35% to 77% of the links have a PDR of less than 90% depending on the used PHY mode (Fig. 6(a)). We cannot identify any clear relationship between the used PHY mode and the PDR. The situation is different in scenario 2 (Fig. 6(b)). Here we see a clear ordering regarding the physical bitrate: with higher bitrate, we have more links with intermediate PDRs. Nearly all links with a bitrate of 27 Mbps or lower have a PDR of almost 1. This is different to 270 Mbps where 55% of the links have a PDR of less than 0.9. Finally, in the results of experiments for the third scenario, the PDR distribution significantly changes when 15 interferer nodes are added to an otherwise empty channel. Now, links with intermediate PDRs are common, i.e. 20% to 75% of the links have a PDR of less than 90% depending on the used PHY mode. Even links using a low bitrate have intermediate PDRs.

In scenario 1, the relative number of links which can be

exploited by MD (links with intermediate PDRs) is between 22% and 40% depending on the used PHY mode. On average only 30% of all links can be exploited by MD, i.e. on average only every third link is suitable for MD. The situation in scenario 2 is even more inappropriate for MD. Here only 1% to 33% of the links have intermediate PDRs depending on the used PHY mode. The average value over all links is 6.7%, i.e. on average every 15th link is suitable for MD. The interference in scenario 3 increases the gain from MD. Here 17% to 50% of the links have intermediate PDRs depending on the used PHY mode. The average value over all links is 34%, which is comparable to scenario 1.

These initial results are very deflating. They show that the expected gain from MD in presence of PHY diversity is low when using 802.11n and is also low when the network is run in 802.11g/a mode. In the latter case, the receiver seems to still make use of the multiple antennas at the receiver side by performing Maximum Ratio Combining (MRC⁵).

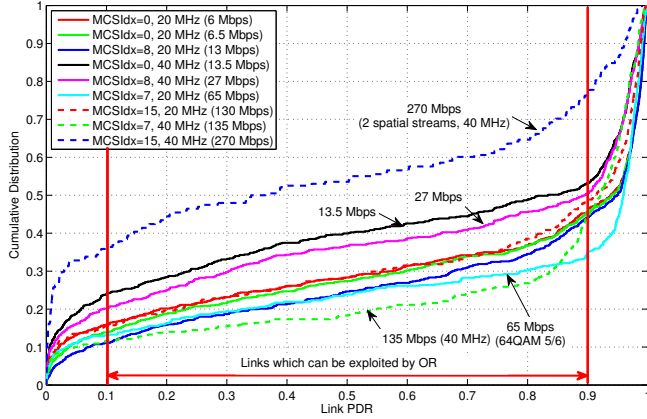
The MD gain to be expected is lower in absence of interference (scenario 2) and is limited to high physical bitrates only where no spatial diversity is applied, i.e. SM instead of SD. This is a crucial difference to the observations made for SISO systems, where a large majority of links with intermediate PDRs was observed [1]. Manually induced interference (scenario 3) increases the number of links with intermediate PDRs. From the results so far, we conclude for stationary networks with robust PHY modes (≤ 27 Mbps) that packet losses at a single receiver can be attributed mainly to interference. This is different to the explanation of Miu et al. [1] which claim that packet losses at a single receiver are due to short term channel fluctuations.

3) *Independence of packet losses*: In the previous section, we learned that there are links with intermediate PDRs in an 802.11n network. The existence of links with intermediate PDRs is only one criterion to achieve a gain from MD. The packet losses at different receivers must also be independent or at least highly uncorrelated. There is no gain from MD for two receivers with dependent packet losses.

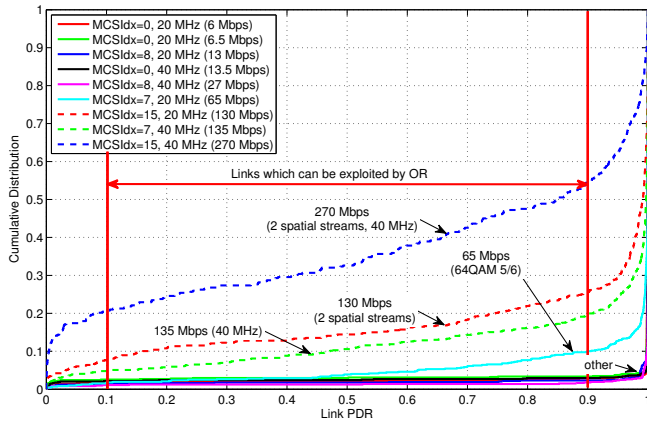
To quantify independence of packet losses, we implemented a simple algorithm that emulates an MD algorithm by combining packet receptions from two receivers to improve the overall packet delivery ratio. This approach is similar to [2]. $PDR(A \cup B)$ represent the number of broadcast transmissions that were successfully received using this algorithm, i.e. using the MD emulation. We compare this experimentally determined PDR with the expected combined PDR $1 - (1 - PDR_A) \cdot (1 - PDR_B)$.

Fig. 7 shows a scatter plot of both the real and expected combined PDR for all possible receiver pairs, i.e. $46 \times \binom{45}{2}$ in our case. If the packet losses at two receivers are independent, both terms are equal and thus all the points in the scatter plot should lie on the diagonal line. However, as shown in the figure, a large part of points does not lie on the line, especially

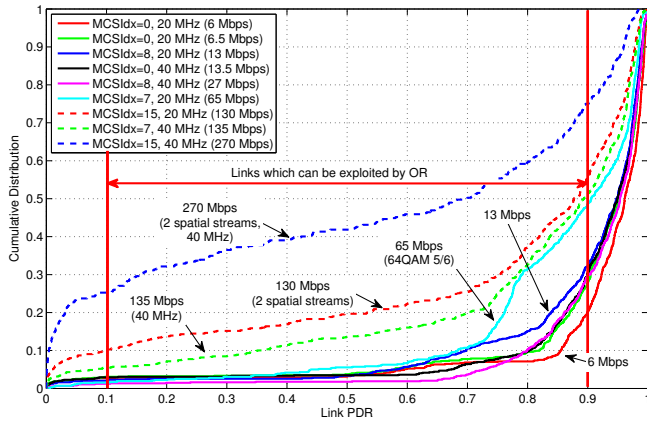
⁵MRC is a technique on the receiver side which optimally combines signals from multiple receiving antennas.



(a) Scenario 1 (channel 6)



(b) Scenario 2 (channel 161)



(c) Scenario 3 (channel 161 + self interference)

Fig. 6. Link Packet Delivery Ratio (PDR).

in scenario 1 and 3. This indicates that the packet losses in 802.11n as well as 802.11g/a are dependent. This is different to the observation made in [2] and similar to our observations made for SISO and 802.11b/g [10]. Especially for low MCSs, the difference between real and expected PDR can be up to 10 percentage points in scenario 1 or even higher in scenario 3. This indicates that the packet loss at different receivers may be correlated under some circumstances. The situation is different for scenario 2. First, as already mentioned, intermediate PDRs are only common for high MCSs. Secondly, we also have

negatively correlated receivers where the actual gain is higher than the expected one. The manually induced interference increases the correlation which is always a positive correlation. This means the actual gain is lower than the expected one.

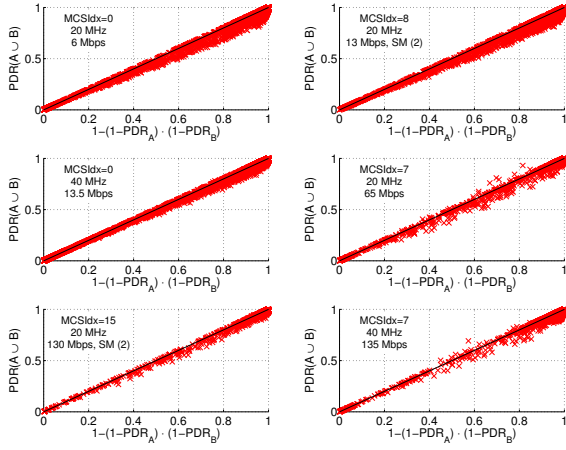
4) *Do spatially co-located receivers have correlated PDRs?*: The previous section showed that packet losses of different receivers can be dependent. In our previous work [10] we evaluated this for SISO systems based on 802.11b/g. We discovered that PDRs of physically close receivers (less than two meters distance) are correlated. This means the probability of multiple link failures can no longer be calculated by simply multiplying error rates.

Therefore, we compared the packet loss correlation between two receivers to the physical distance of the two receivers. As a measure for correlation, we calculated the difference between expected PDR (assuming independent packet losses) and the actual PDR $PDR(A \cup B)$ (emulating OR). Furthermore, we classified a receiver pair according to the spatial separation between them; both receivers are either (i) in the same room or (ii) in different rooms and the Euclidean distance between both receivers is either (iii) smaller than 5 m or (iv) larger than 10 m. The results are shown in Fig. 8.

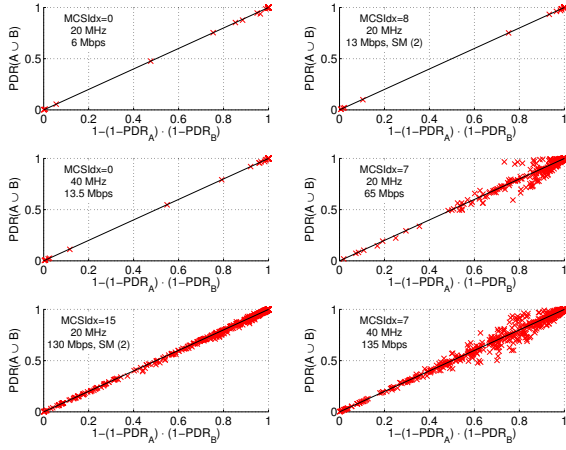
In scenario 1, the difference is larger for spatially close receivers, e.g. the difference between expected and actual MD gain of more than 1 percentage points: 10% of the cases for high spatial separation between both receivers (≥ 10 m) and 43% of the cases for spatially close receivers (same room). The situation is even more pronounced in scenario 3 where the manually induced interference corrupts the packets of closely-located receivers. This results in highly correlated packet losses. In this case, the difference between expected and actual MD gain can be very high, e.g. up to 15 percentage points for 270 Mbps and same room receivers. The results are different in the interference-less scenario 2. Only with 270 Mbps, there are a very small number of correlated receiver pairs where the spatial separation between receivers has a (only small) impact.

5) *What is the gain from MD compared to choosing the best neighbor only?*: Finally, we want quantify the performance gains achievable with MD compared to choosing only the best neighbor. Therefore, we compare $PDR(A \cup B)$ (i.e. the rate of packets received by at least one of the receivers, i.e. as MD would receive) with the PDR of the best of the two receivers ($\max(PDR_A, PDR_B)$). The latter represents the PDR of the best next hop as used by traditional single-path routing.

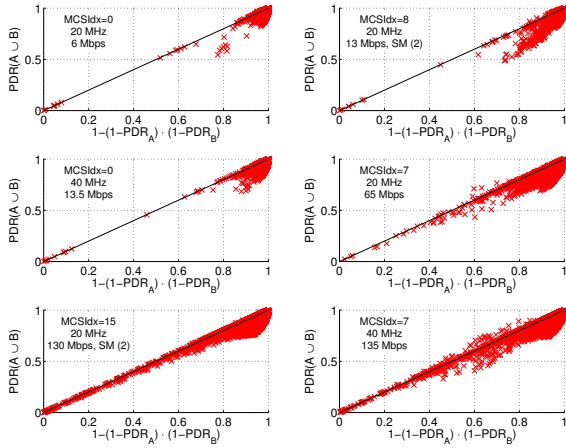
The difference between both quantities is depicted in Fig. 9. In scenario 2, the MD gain is negligible (Fig. 9(b)). For the highest bitrate the gain is less than 5 percentage points in 87% of the cases, i.e. only 13% of all evaluated receiver pairs are suitable for MD. For lower bitrates the gain is even lower, e.g. for ≤ 27 Mbps there is no visible gain. This can be explained by the fact that scenario 2 contains only a few links with intermediate PDRs (ref. to Fig. 6(b)). The situation in scenario 1 is similar (Fig. 9(a)). Regardless of the PHY mode, less than 11% of the receiver pairs offer an MD gain of more than 5 percentage points. The only difference is that a gain can also be achieved with low bitrates. In scenario 3, the results are



(a) Scenario 1 (channel 6)



(b) Scenario 2 (channel 161)



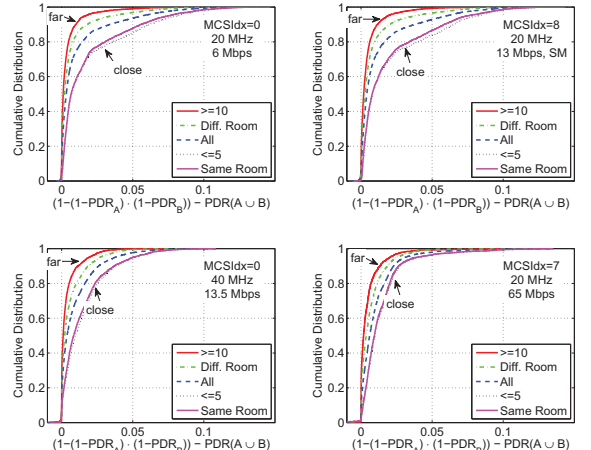
(c) Scenario 3 (channel 161 + self interference)

Fig. 7. Expected vs. actual MAC diversity gain.

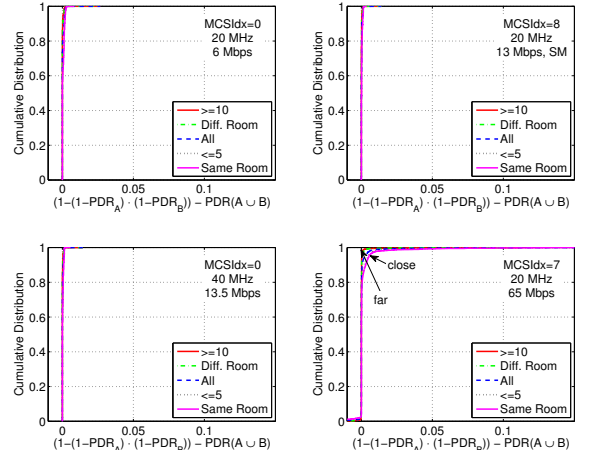
similar to scenario 1: the gain from MD is small. This means that also in the presence of interference, the gain from MD would be small.

V. CONCLUSION AND FUTURE WORK

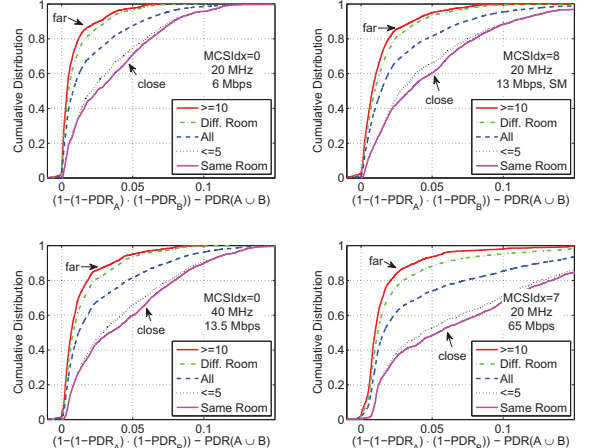
In this paper we analyzed the gain from MAC diversity as offered by OR in the presence of physical diversity as



(a) Scenario 1 (channel 6)



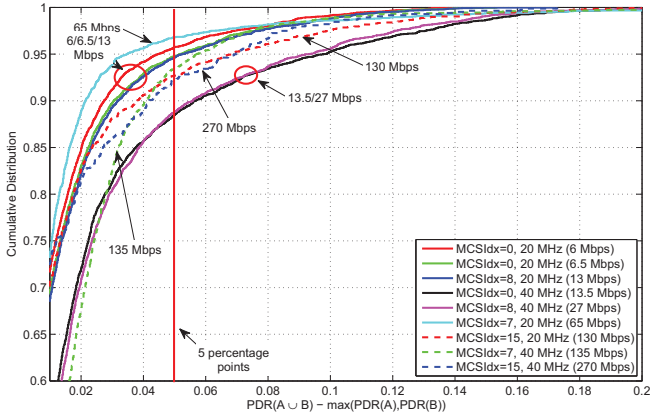
(b) Scenario 2 (channel 161)



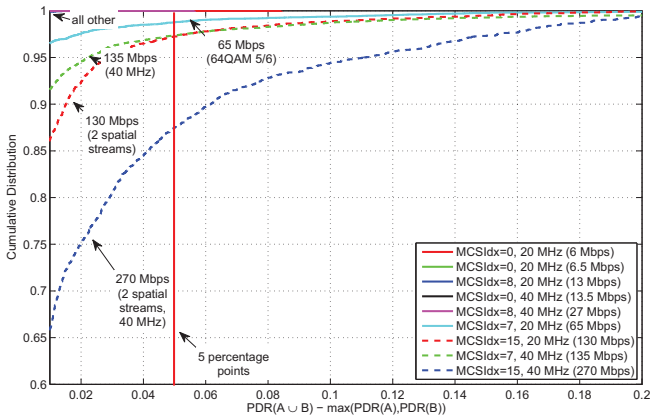
(c) Scenario 3 (channel 161 + self interference)

Fig. 8. Impact of spatial separation between both candidates.

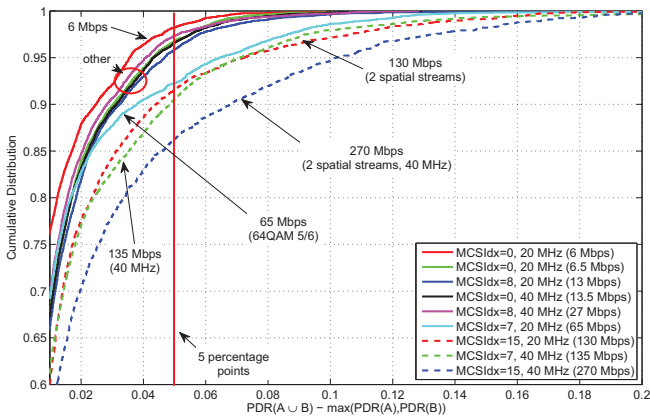
provided by MIMO systems based on 802.11n. Therefore, we analyzed the nature of packet losses. Our experimental results obtained from an IEEE 802.11n indoor testbed show that: i) links with intermediate PDR which can be exploited by MD are scarce, i.e. on average only 30% and 6.7% of all links



(a) Scenario 1 (channel 6)



(b) Scenario 2 (channel 161)



(c) Scenario 3 (channel 161 + self interference)

Fig. 9. Gain from MD compared to choosing the best neighbor only.

can be exploited by MD when using an interference-prone and an interference-free channel respectively, ii) we cannot conclude that packet losses are fully independent, i.e. spatially co-located receivers have correlated PDRs which is especially the case when using an interference-prone channel. This is similar to our observations made for SISO systems based on 802.11b/g [10], iii) the gain from MD is negligible regardless whether the interference-prone or an interference-free channel is used, i.e. less than 5 percentage points for PDR in 90% of the cases compared to choosing the best neighbor only. This

is different to the observations made with SISO systems, e.g. 802.11b/g [1], as well as first studies of 802.11n [2].

As future work we consider the following. First, we want to repeat our experiment in an outdoor environment as well as using 802.11n hardware from other vendors. Second, we want to analyze the nature of bit errors in packets with incorrect Cyclic Redundancy Check (CRC) checksum. In the past we already showed that in case of 802.11b/g the bit errors over different receiver nodes were suitably distributed, so that a correction was possible by combining OR with Network Coding techniques [11]. Finally, we want to holistically re-evaluate existing OR protocols in a 802.11n-based multi-hop mesh network allowing us to determine the gain from OR that is not attributed to MD (i.e. multi-path diversity).

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