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Analysing Capacity Improvements in Wireless Networks by Relaying

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Contents

Abstract

In infrastructure-based wireless networks, the total transmission capacity achievable at an access point is an important metric for system performance. In this paper, we present an analytical investigation of the use of relaying in wireless cells in order to improve the total goodput at an access point. A simple scenario of two cells is considered, formulas for SINR, packet error rate, and goodput are derived and numerically evaluated for both the standard direct communication case and the use of relaying terminals. We will show that the path loss coefficient and the physical location of terminals are the most important parameters and that for realistic scenarios, relaying can improve the total goodput of a cell by over 40%. Moreover, for most realistic scenarios, relaying is never worse than direct communication while providing a fairer sharing of bandwidth between terminals within a cell.

1 Introduction

The large amounts of money that have recently paid in auctioning of UMTS frequency bands has shown that radio spectrum is a scarce and valuable resource. Given a fixed amount of spectrum, maximizing the capacity for successfully transporting user traffic is, hence, a question of great practical importance. Many different approaches have been used to improve the capacity (e.g., coding and modulation or appropriate medium access techniques) and recently, the use of relaying has been considered not only to extend the coverage of a cellular (i.e., access point-based as opposed to ad-hoc) network, but also for capacity improvements.

The fundamental impediment of large capacity is errors in the transmission. One of the main causes of transmission errors is interference, and reducing interference represents one reason why relaying could improve capacity: In a direct communication scenario, every terminal is communicating directly with the access point. While this does not cause problems for terminals that are close to the base station, terminals that are far away (called “far” terminals) need to use an overproportionally large amount of transmission power (due to the non-linear decay of received power over distance, cp. Section 3). This large transmission power, in turn, will create interference in the neighboring cells (using the same frequency band). Even though such cells will be some distance away (using typical frequency reuse schemes), the fact remains that reducing the transmission power of terminals close to the edge of cell holds a big promise for reducing interference and, hence, improving capacity.

However, directly reducing transmission power will result in a much higher error rate when attempting to communicate directly with the access point. Communication with a terminal positioned in between should still be possible. Such an intermediate terminal could serve as a relaying point. But this relaying terminal now has to transmit a higher traffic load, which is in general not possible at the bit rate of the modulation it is currently using. To overcome this, a “faster” modulation with a high bit rate needs to be used. Normally, a higher bit rate would incur the penalty of higher error rates at the same level of noise and interference, but as the level of interference is reduced (far terminals reduce their power), this might actually be feasible.

It is this tradeoff between lower interference by reduced transmission power at the border of cells on the one hand and increased error rate due to the need to increase data rate in the interior of a cell on the other hand that this paper investigates. For a simple model, the total goodput of a cell is analyzed and numerically evaluated. We will show that for many relevant parameter settings the relaying case is always at least as good as the direct communication case and that improvements of over 40 % can be achieved.

After considering some other work related to capacity increase in wireless networks in Section 2, the model itself is introduced in Section 3. As the present work is part of a project [1] that uses HiperLAN/2 as a case study of a wireless network technology, this analysis here uses a simple time division multiple access model and uses relationships between interference and errors that are motivated by the HiperLAN/2 technology. The goodput achievable in this model using both direct and relay communication is analyzed in Section 4 and numerical evaluations are shown in Section 5. The results are discussed and conclusions are drawn in Section 6, which also outlines prospects for future research.

2 Related Work

As this paper is part of a project that uses HiperLAN/2, we are particularly interested in using interference-to-error-rate mappings that describe the actual behavior of a HiperLAN/2 system. The only numbers available are those published by KHUN-JUSH et al. [6]. Their model is assumed to have large office environment with non-line-of sight propagation. The computation we have for PER at a given C/I is obtained from the result of simulation they run on this channel model for all physical layer modes. Their result shows that the C/I required for a certain error rate increases with bit rate with the exception of 9 Mbit/s. They also showed the ideal achievable link throughput in C/I distribution for the different physical layer modes-the code rate and modulation schemes.

SHEPARD showed a decentralized channel access scheme for scalable packet radio network that is free of packet loss [7]. In this scheme, a power control algorithm is used to reduce the excessive power used for transmitting to stations which are closer than the maximum range and to transmit with same average power density as before keeping average signal to noise ratio the same. With reduced power, as long as the low power level can still deliver a sufficient signal to noise ratio at the receiving station, interference to other stations can be reduced and the signal to noise ratio in receivers at other station can also be increased. Minimum-energy routing is also used in the channel access scheme mentioned to route packets traveling more than a distance of $2\rho^{-1/2}$, where ρ is average distribution density of stations, through intermediate stations to minimize packet loss. One of the criteria used to determine routes is choosing the nearest hop, which produces less interference. We also applied these basic ideas to our relaying network and opted for capacity improvement. The relaying terminals, in our case, are chosen to be the ones close to the access point and they transmit not only routed packets but also their own packet with faster modulation, to the access point.

With regard to the capacity of wireless networks, GUPTA and KUMAR [5] have studied the capacity of randomly located ad-hoc networks. Their result shows that for n identical, radomly located nodes, the maximum acheivable throughput under optimal circumstances is $\frac{1}{\sqrt{n}}$ times the transmission rate and as the number of nodes n per unit area increases, the throughput decreases accordingly. GROSSGLAUSER and TSE [4] used a similar situation as in Gupta and Kumer but introduced mobility into the model and showed how the capacity of this wireless ad-hoc network can be increased. Their result is, in fact, in sharp contrast to that of Gupta and Kumer since the average long-term throughput they obtained can be kept constant even as the number of nodes n per unit area is increased.They also showed that a single relay is sufficient to use the entire throughput capacity of the network within the limits of their inteference model. However, the increase of the capacity is at the cost of considerable delay.

Recently, BRONZEL et al. [2] have also shown how the capacity of a single-relay network (called “single hop relay” in their paper) can be increased by reducing the interference in the network. They investigated the achievable average transmit power reduction and capacity gain that results from using mobiles as relay stations for other terminals. Their result shows that the use of single hop relay (SHR) in a mobile network generally reduces the total transmit power. Furthermore, SHR provides an increase in achievable capacity gain of around 20% for uplink transmission in a CDMA system. However, this achievable gain decreases with increase of pathloss exponent. Though our treatment is basically on TDMA system, we demonstrated that the achievable throughput capacity gain increases when relay communication is used.

3 Model Definition

For an analytical investigation of relaying, we are considering a very simple model: two cells, each with an access point and two mobile terminals. Our goal is to check if and which circumstances the total goodput (the amount of successfully transfered bits from both terminals per unit time) is increased when relaying is used.

To simplify the analysis, a symmetric layout of access points and cells has been chosen, which is shown in Figure 1: all six terminals are located on a single line, the distance between terminals within a cell is indicated by d, the distance between the two outmost terminals of each cell is D (the separation of the cells). All terminals use the same communication channel, as we are interested in the improved goodput resulting from reduced interference.

The analysis will only consider the uplink communication from mobile terminals to access points. To cross a distance of d, a terminal uses a transmission power of P_T (in Watts), to cross $2d$, P'_T is used. The path loss model relating transmitted and received power P_T and P_R is simple and depends only on distance x and path loss coefficient α,

$$P_R = \frac{P_T}{x^\alpha} \tag{1}$$

The actual packet error rate results from the received power, the noise N (in Watt) and the interference from other transmissions in the same channel (we are ignoring adjacent channel interference). This relationship (from C/I to PER) is described in [6] for all of HiperLAN/2’s modulations. We are using a simple exponential curve fitting: let i be the index of the modulation to be used, $s = 10 \log_{10} \mathrm{SINR}$, the SINR in dB, the packet

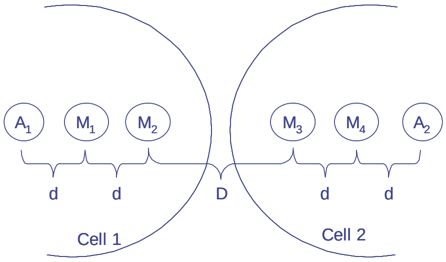

Figure 1: Scenario description

error rate is given as

$$\mathrm{PER}(s, i) = 10^{a_i s^2 + b_i s + c_i} \tag{2}$$

(with appropriate cutoff to ensure that the PER is between 0 and 1), where a_i, b_i, and c_i are defined in Table 1 (which also shows name and nominal bit rate (NBR) for these modulations). An advantage of this approach is that the particular environment studied in [6] is reflected quite accurately, but the disadvantage is we are applying these same numbers to scenarios which they were not originaly intended to discribe. A more general characterization of the relationship between noise, interference, and packet errors would be highly desirable to increase the validity of our results. Nevertheless, we believe that this approximation should be close enough to provide an intial understanding of the relaying capacity problem.

Index i	Modulation (code rate)	NBR $(\mathrm{MBit/s})$	a_i	b_i	c_i
1	BPSK (1/2)	6	-0.00826140426805	-0.06376668709407	-0.19668486235428
2	BPSK (3/4)	9	-0.00691007462078	-0.01170647235394	-0.10819588784435
3	QPSK (1/2)	12	-0.00961459243554	+0.00515845543333	-0.14211581761582
4	QPSK (3/4)	18	-0.00689529575429	+0.02765247907588	-0.10966369423267
5	16QAM (9/16)	27	-0.00783459997375	+0.08195372387766	-0.29870707399130
6	16QAM (3/4)	36	-0.00703381983645	+0.11297740455648	-0.53792530792585
7	64QAM (3/4)	54	-0.00623228999252	+0.15392834195885	-0.99488471979605

Table 1: Parameters for C/I to PER interpolation

As we are interested in the use of time-division multiple access techniques, a communication schedule needs to be defined for the direct a well as the relaying case in both cells. Section 4 will described the schedules in detail. As a worst-case scenario, we are here considering the simultaneous occurrence of the uplink phase in both cells. It should also be mentioned that we are only taking into account the actual data transmission phase; overhead needed to construct schedules (and to determine relaying stations) is not considered.

Finally, all terminals are assumed to transmit at the maximum possible data rate to the access point, by only considering the nominal capacity of a given transmission. Otherwise, the net bandwidth would correspondingly be reduced due to protocol overhead. Intra-cell traffic is not also considered. This traffic assumption is actually conservative as it puts considerable requirements on the relaying node, which has not only to transmit its own traffic but also the other node's traffic. This results in the need to use faster modulations between inner terminal and access point (see Section 4) with inferior error behavior. Under lower load, this could be avoided, which should in turn improve the performance of relaying.

	Cell 1	Cell 2
Time slot 1	$M_1 \to A_1$	$M_3 \to A_2$
Time slot 2	$M_2 \to A_1$	$M_4 \to A_2$

Table 2: Schedule for direct communication

4 Analysis

4.1 Direct communication

4.1.1 Choosing transmission power

According to the relation shown in Equation (1) and assuming the SINR of the "near" and the "far" terminals to be identical, we may have the following relation to choose an approperiate transmission power.

$$\frac{\frac{P_T}{d^\alpha}}{N} = \frac{\frac{P'_T}{(2d)^\alpha}}{N} \tag{3}$$

which is equivalent to $P'_T = 2^\alpha P_T$. This value for P'_T will be used subsequently.

4.1.2 Determining communication schedule

In order to compute the goodput, the actual interference of the two cells must be computed. This is only feasible to do when an actual communication scheduled is known. The uplink phase considered here can be scheduled using two time slots, one for the inner, one for the outer terminals. To keep the symmetry between the two cells, inner and outer terminals of the two cells operate in alternate slots. As both terminals are assumed to have the same load, both can use the same modulation. The resulting schedule is shown in Table 2.

4.1.3 Determining SINR

Based on this schedule, the actual SINR values can be computed directly.

Transmitting from M_1 to A_1:

$$\mathrm{SINR}_{M_1 \to A_1} = \frac{\frac{P_T}{d^\alpha}}{N + \frac{2^\alpha P_T}{(2d+D)^\alpha}} \tag{4}$$

Transmitting from M_2 to A_1:

$$\mathrm{SINR}_{M_2 \to A_1} = \frac{\frac{2^\alpha P_T}{(2d)^\alpha}}{N + \frac{P_T}{(3d+D)^\alpha}} \tag{5}$$

The SINRs for the second cell are symmetric.

4.1.4 Determining PER and goodput

Based on these SINR values, the actual PERs can be determined, using Equation (2), taking into account the employed modulation j (identical for both terminals). Based on this PER, the goodput GP for a particular terminal can be approximated as $\mathrm{GP} = (1 - \mathrm{PER})$*(modulation's nominal data rate)*. This assumes a very simple link layer which does not provide any ARQ protocols.

However, since the two terminals have to share the channel with each other, the nominal data rate needs to be divided by two (without considering a downlink phase, which would further linearly scale down the goodput). Hence, the goodput is (using the PER Equation (2)):

	Cell 1	Cell 2
Time slot 1	$M_1 \to A_1$ (fast modulation)	$M_3 \to M_4$
Time slot 2	$M_2 \to M_1$	$M_4 \to A_2$ (fast modulation)

Table 3: Schedule for relay communication

$$\mathrm{GP}_{M_1 \to A_1} = (1 - \mathrm{PER}(10 \log_{10}(\mathrm{SINR}_{M_1 \to A_1}), j)) \frac{\mathrm{NBR}_j}{2} \tag{6}$$

$$\mathrm{GP}_{M_2 \to A_1} = (1 - \mathrm{PER}(10 \log_{10}(\mathrm{SINR}_{M_2 \to A_1}), j)) \frac{\mathrm{NBR}_j}{2} \tag{7}$$

Cell 1's total goodput is the sum of goodput of terminal 1 and 2 (symmetric for cell 2). Examples for some concrete settings of parameters are shown in Section 5.

4.2 Relay communication

4.2.1 Choosing transmission power

In this relay communication model, all the data communication is across a distance d only, and hence, only a uniform transmission power P_T is used.

4.2.2 Determining communication schedule

The schedule for this setup is slightly complicated: on the one hand, only two time slots can be used to communicate the traffic of both mobile terminals within a cell to the access point.[1] On the other hand, the relaying stations M_1 and M_4 should transmit both their own traffic as well as the relayed traffic of M_2 and M_3, respectively. It is evidently not possible to use the same amount of time and the same modulation as in the previous case (when both stations transmit at a bandwidth close to the maximum possible bandwidth of a chosen modulation). Hence, to transmit from the relay station to the access point, a "faster" modulation has to be used. Here, we assume that for this communication link, a modulation at least twice as fast as for the communication between normal mobile terminal and relay terminal is used. Thus, the actual schedule would look like in Table 3.

This schedule is actually a pessimistic approximation. The relay terminal is always using the faster, more error-prone modulation, whether or not the outer terminal has sent any data that is to be relayed to the access point, while in the particular traffic model assumed here, the outer terminal always has data to sent, this is unlikely to be the case in realistic scenarios. Hence, adding a mechanism that uses faster modulation between relay and access point only when necessary should again improve the error behavior of this link. Such a mechanism, however, could imply additional signaling overhead and delay– we leave this problem for further study.

4.2.3 Determining SINR

Based on the schedule, the actual SINR values can be computed directly.

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[1] If more than two time slots were used, it would be difficult to see any increase in capacity — however, this might be feasible as the PERs might drop considerably, so this is left for further study.

Transmitting from M_1 to A_1:

$$\mathrm{SINR}_{M_1 \to A_1} = \frac{\frac{P_T}{d^\alpha}}{N + \frac{P_T}{(2d+D)^\alpha}} \tag{8}$$

Transmitting from M_2 to M_1:

$$\mathrm{SINR}_{M_2 \to M_1} = \frac{\frac{P_T}{d^\alpha}}{N + \frac{P_T}{(2d+D)^\alpha}} \tag{9}$$

The SINRs for the second cell are symmetrical.

The main different between the direct and the relay case is now apparent: lower transmission power is used close to the border of a cell, improving the interference situation, yet on the downside, faster and more error-prone modulations need to be used close to the interior of a cell.

4.2.4 Determining PER and goodput

Determining the goodput is here slightly complicated than in the direct case as we have to deal with two different modulations and communication going over two different hops.

Consider first the goodput for terminal M_1, assuming that M_1 uses modulation i having nominal bit rate NBR_i. As M_1 is only transmitting for half the time, NBR_i has to be divided by two. Moreover, has only half the amount of data in transmits in one time slot has originated for M_1, NBR_i actually must be divided by four. The total goodput for M_1 is hence

$$\mathrm{GP}_{M_1 \to A_1} = (1 - \mathrm{PER}(10 \log_{10}(SINR_{M_1 \to A_1}), i)) \frac{\mathrm{NBR}_i}{4} \tag{10}$$

The goodput for M_2 also depends on the NBR it is using when communicating with M_1, using modulation index j. Similarly to the direct case, M_2 can only transmit half the time, cutting the nominal bit rate in half as well. As we have assumed that $\mathrm{NBR}_i \geq 2\mathrm{NBR}_j$, the bandwidth between M_1 and A_1 should not limit the goodput of M_2. More complicated is the error handling: a packet from M_2 needs to be transmitted successfully between M_2 and M_1 as well as between M_1 and A_1. Hence, the goodput for M_2 is:

$$\mathrm{GP}_{M_2 \to A_1} = (1 - \mathrm{PER}(10 \log_{10}(\mathrm{SINR}_{M_1 \to A_1}), i))(1 - \mathrm{PER}(10 \log_{10}(\mathrm{SINR}_{M_2 \to M_1}), j)) \frac{\mathrm{NBR}_j}{2} \tag{11}$$

Just like in the direct communication case, these numbers would have to be downscaled correspondingly for inclusion of a downlink phase. However, as this needs to be done in both case, this scaling factor cancels out when looking at the ratio of the total goodput in both cases and is hence not considered here.

5 Numerical Evaluation

We have examined the capacity of both direct and relay communication of the wireless network model using numerical solutions of the equations derived in Section 4. The numerical solution obtained depends on the mobile terminal separation d and the intercell separation D for various values of transmission power P_T and path loss coefficient α as well as on the noise level N. Our evaluation is, thus, based on the PER, the SINR and the goodput at both near and far terminal, using either direct or relay communication. One representative example of such results is shown in Table 4 for direct communication, in Table 5 for relay communication. In any of the cases the nominal bit rate we assumed is 6 Mbit/s for communication between source and relay terminals as in relaying case or source terminals to access point as in the direct communication case. However, 12 Mbit/s is used for "faster" modulation scheme while the relaying terminal is communicating with the access point.

	$M_1 \to A_1$	$M_2 \to A_1$
SINR	2.907287	16.321736
PER	0.353264	0.000365
m Goodput	1.940209	2.998906
Total goodput	4.939115	

Table 4: Results for direct communication, using $P_T = 0.1\mathrm{W}$, $\alpha = 3$, $N = 1.64 \times 10^{-13}\mathrm{W}$, $d = 100\mathrm{m}$ and $D = 50\mathrm{m}$ (goodput in MBit/s).

	$M_1 \to A_1$	$M_2 \to M_1(A_1)$
SINR	11.938089	11.938089
PER	0.035417	0.007323
Goodput	2.893749	2.872559
Total goodput	5.766307	

Table 5: Results for relaying communication, using $P_T = 0.1\mathrm{W}$, $\alpha = 3$, $N = 1.64 \times 10^{-13}\mathrm{W}$, $d = 100\mathrm{m}$ and $D = 50\mathrm{m}$. Goodput describes $M_2 \to A_1$ (goodput in MBit/s).

In comparison, the goodput from the far terminal M_2 to the access point suffers slightly when using relay communication: in direct communication, M_2's communication is only interfered with by M_4, which is far away from A_1 and uses low transmission power anyway. Hence, there is little potential to ameliorate an already good situation for M_2 and indeed, the goodput of M_2 does decrease slightly. For M_1 on the other hand, the direct communication case is rather bad: terminal M_3 is comparably close to A_1 and uses a large transmission power. Reducing M_3's power should and does considerably increase the goodput of M_1 even though this communication must happen at a faster and more error-prone modulation. In total, the slight reduction of M_2's goodput is more than compensated by the increase in goodput of M_1 when considering the total goodput of a cell — total goodput is about 16% better when using relaying. Additionally, the relaying case actually results in a fairer distribution of resources than the direct communication, which is an additional benefit.

The following graphs give an overview of the ratio of the total goodput in a cell between direct and relaying communication. Ratios with values larger than 1 indicate a better relaying performance. The graphs are shown for cases with fixed transmission power P_T and varying α as well as for fixed α and varying transmission power. Evidently, the impact of the transmission power is negligible with respect to the ratio of the capacities. This is mainly due to the way the transmission power is chosen, and remains to be an area for additional investigations.

It is interesting to note the behavior of the capacity ratio for α values between 2 and 3 in (Figures 7 to 17). For for smaller α's, direct communication is practically better than relaying. Yet for values of α greater than about 2.3, relaying is never worse than direct communication, and as α continues to grow, the potential gain of relaying also increases, reaching up to 40% in the best example shown in Figure 2 for $\alpha = 4$.

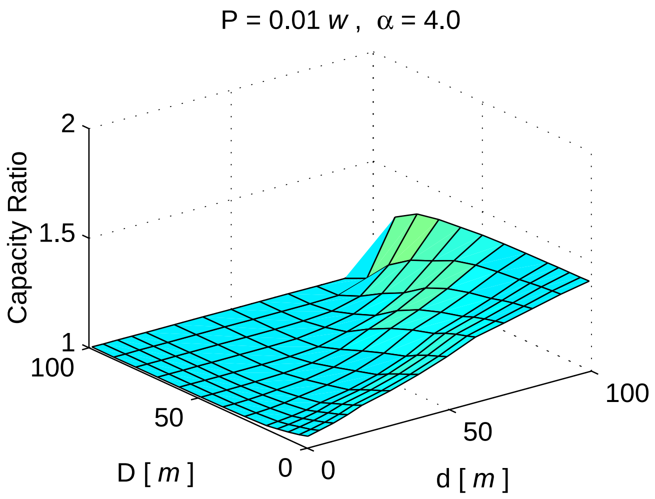

Figure 2: Ratio of total goodput for $\alpha = 4$ and $P_T = 0.01\mathrm{W}$

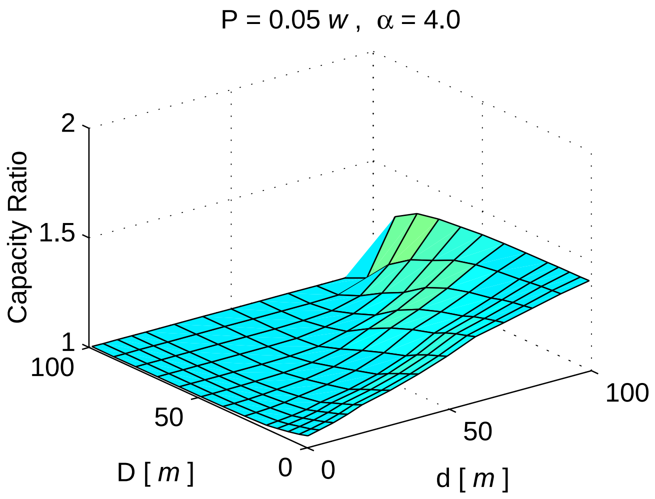

Figure 3: Ratio of total goodput for $\alpha = 4$ and $P_T = 0.05\mathrm{W}$

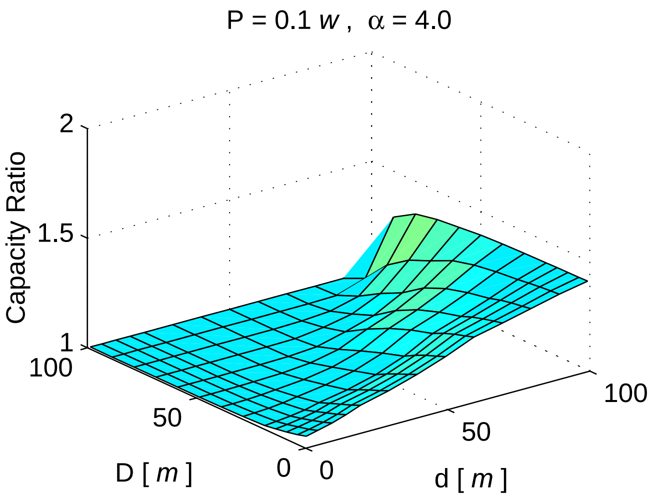

Figure 4: Ratio of total goodput for $\alpha = 4$ and $P_T = 0.1\mathrm{W}$

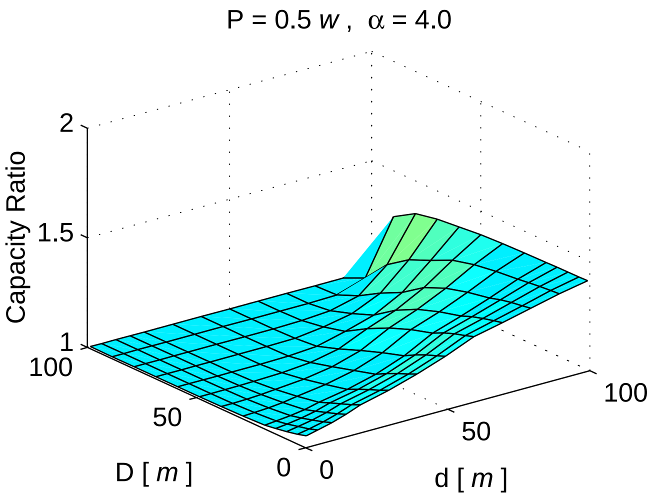

Figure 5: Ratio of total goodput for $\alpha = 4$ and $P_T = 0.5\mathrm{W}$

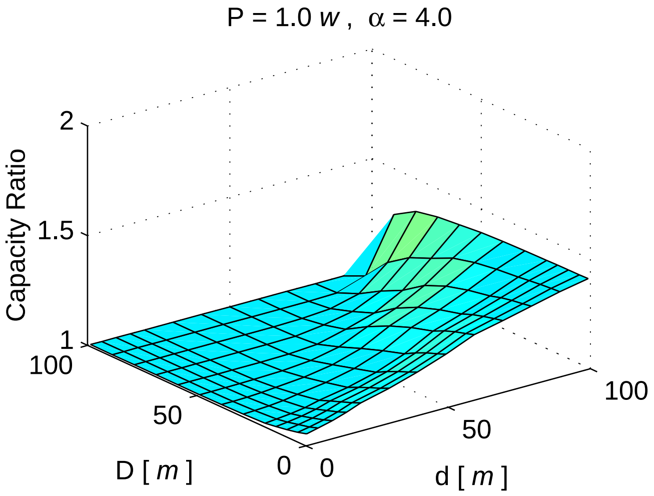

Figure 6: Ratio of total goodput for $\alpha = 4$ and $P_T = 1\mathrm{W}$

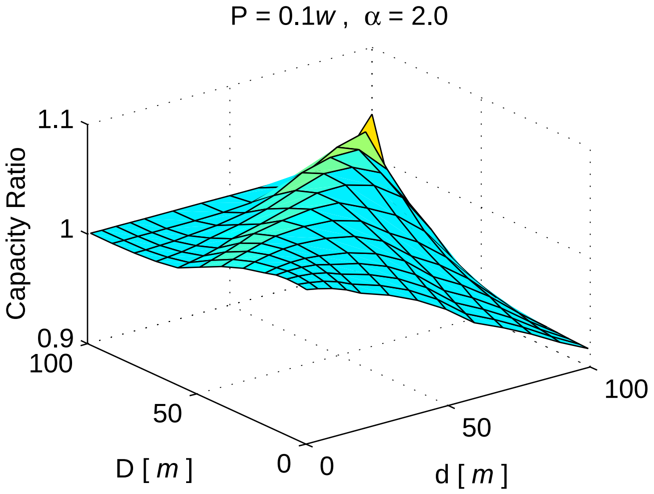

Figure 7: Ratio of total goodput for $\alpha = 2$ and $P_T = 0.1\mathrm{W}$

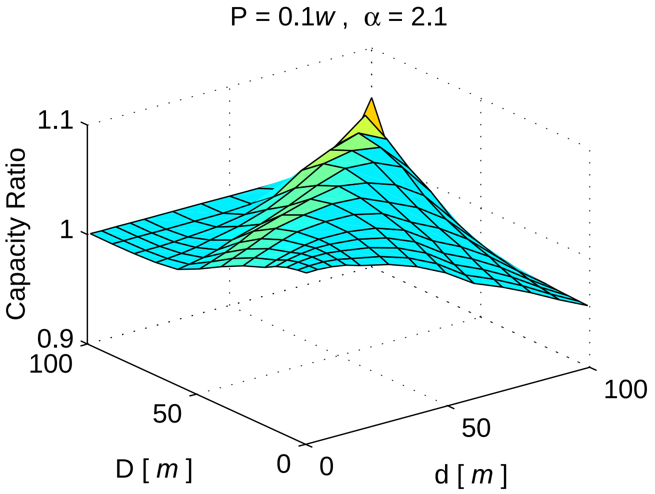

Figure 8: Ratio of total goodput for $\alpha = 2.1$ and $P_T = 0.1\text{W}$

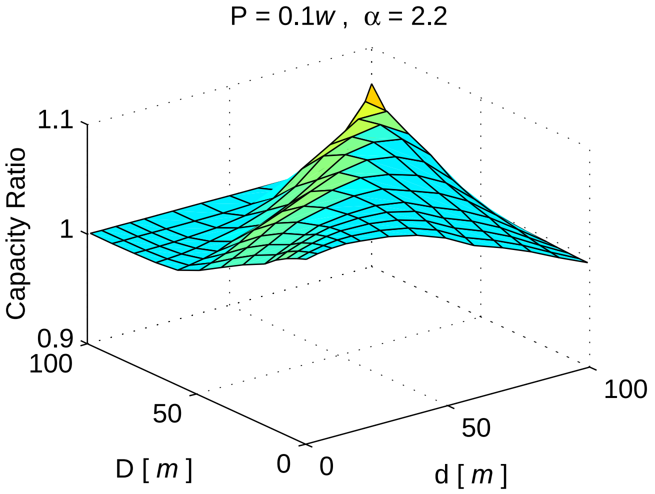

Figure 9: Ratio of total goodput for $\alpha = 2.2$ and $P_T = 0.1\text{W}$

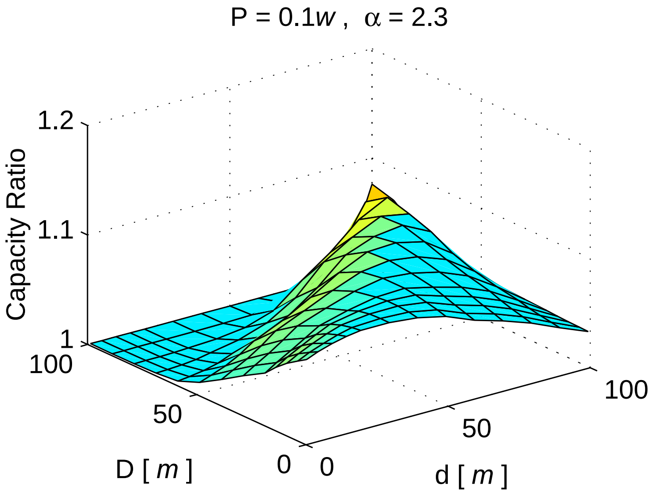

Figure 10: Ratio of total goodput for $\alpha = 2.3$ and $P_T = 0.1\text{W}$

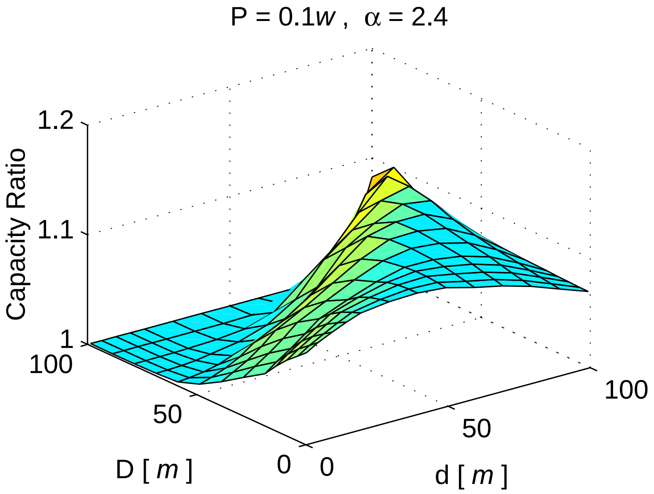

Figure 11: Ratio of total goodput for $\alpha = 2.4$ and $P_T = 0.1\text{W}$

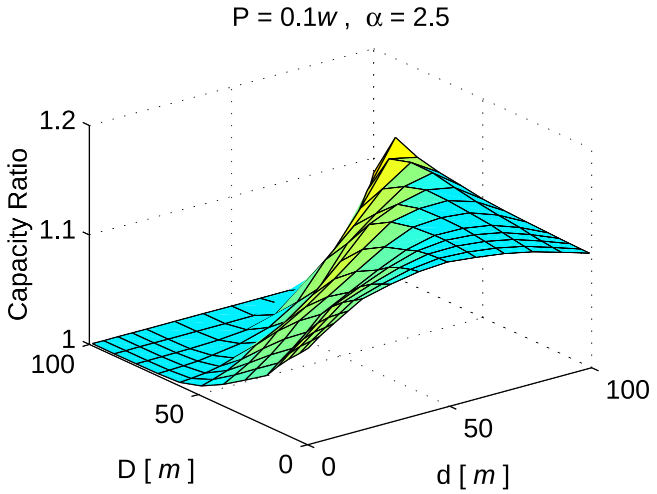

Figure 12: Ratio of total goodput for $\alpha = 2.5$ and $P_T = 0.1\mathrm{W}$

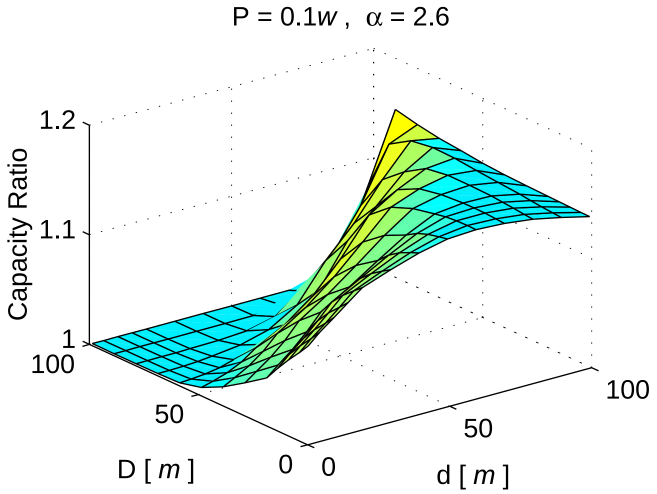

Figure 13: Ratio of total goodput for $\alpha = 2.6$ and $P_T = 0.1\mathrm{W}$

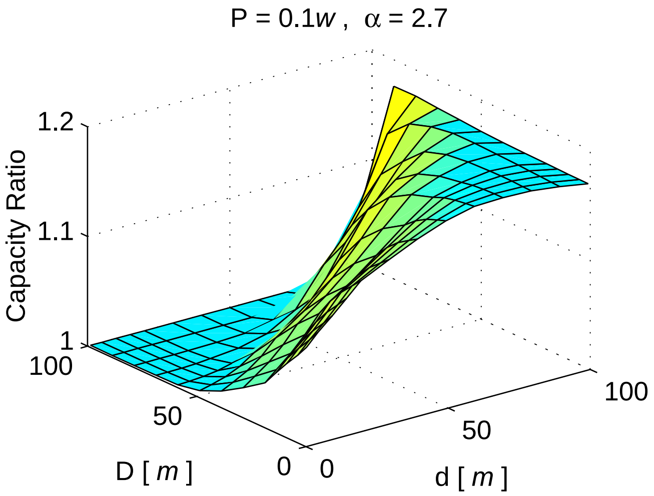

Figure 14: Ratio of total goodput for $\alpha = 2.7$ and $P_T = 0.1\text{W}$

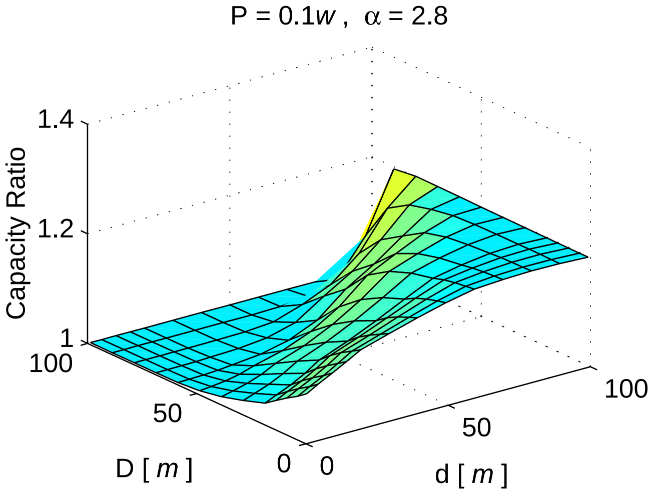

Figure 15: Ratio of total goodput for $\alpha = 2.8$ and $P_T = 0.1\text{W}$

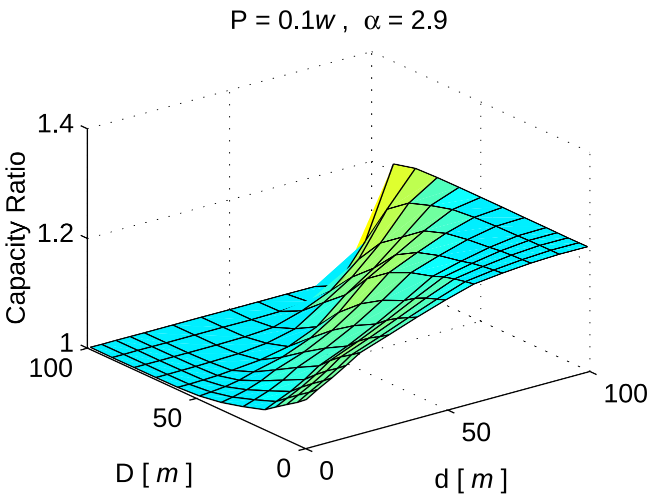

Figure 16: Ratio of total goodput for $\alpha = 2.9$ and $P_T = 0.1\mathrm{W}$

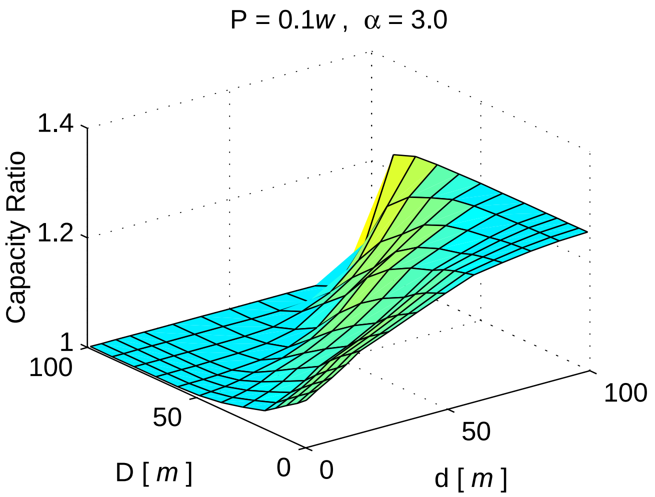

Figure 17: Ratio of total goodput for $\alpha = 3$ and $P_T = 0.1\mathrm{W}$

The ratio of the goodput obtained from the individual terminals M_1 and M_2 can be used as one possible metric for the measure of fairness of the communication. Ideally, this ratio should be 1, so that both terminals will share the same amount of useable bandwidth. It is easy to see from Figures 18 to 21 that, the relaying offers a better fairness metric than the direct communication. For the relay communication, goodputs at both terminals are at most 15% apart from each other and usually much closer, whereas for direct communication, the goodput can differ by over a factor of 2.5.

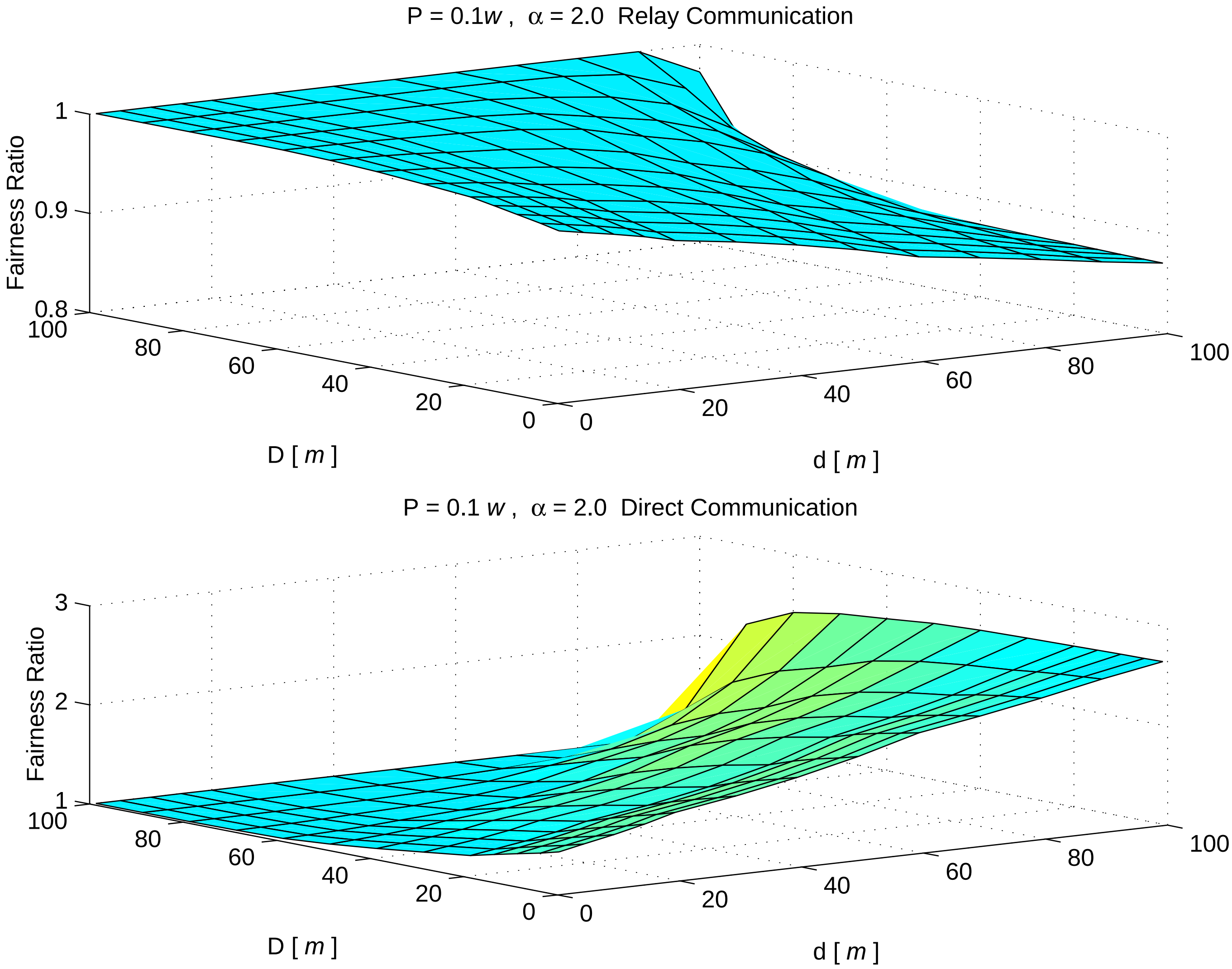

Figure 18: Comparison of the ratios of goodput of $M_2 \rightarrow M_1$ for direct and relay communication, $\alpha = 2$, $P_T = 0.1\text{W}$

It is also possible to conclude that relaying is particularly beneficial when considering scenarios where mobile terminals are far away from their access points, and also for the case of cells located close to each other. While the last case is usually avoided with spatial reuse, it might occur more often when relaying within a cell is considered using different channels (requiring a larger number of frequency than might be available in usual spatial reuse patterns).

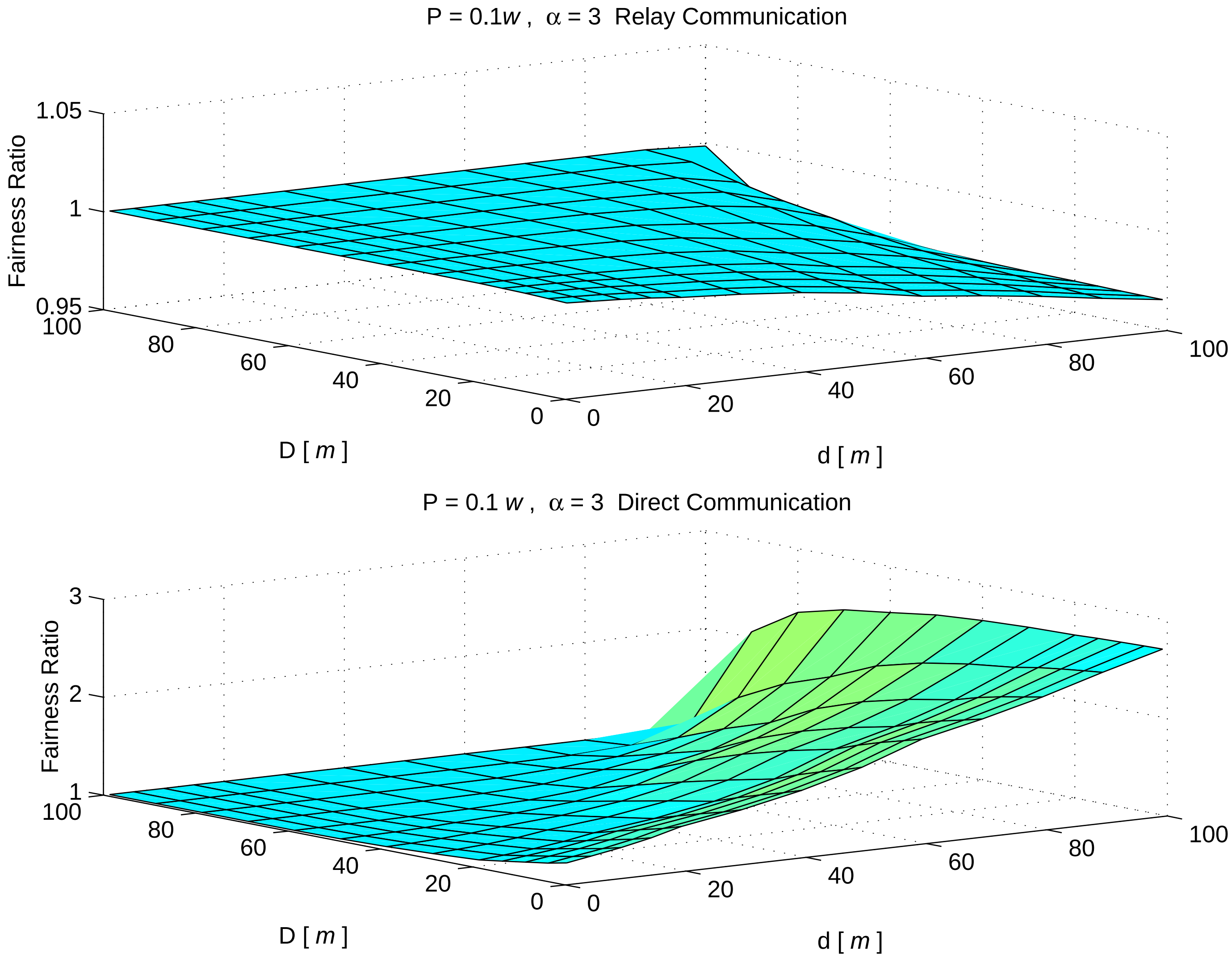

Figure 19: Comparison of the ratios of goodput of $M_2 \rightarrow M_1$ for direct and relay communication, $\alpha = 3$, $P_T = 0.1\mathrm{W}$

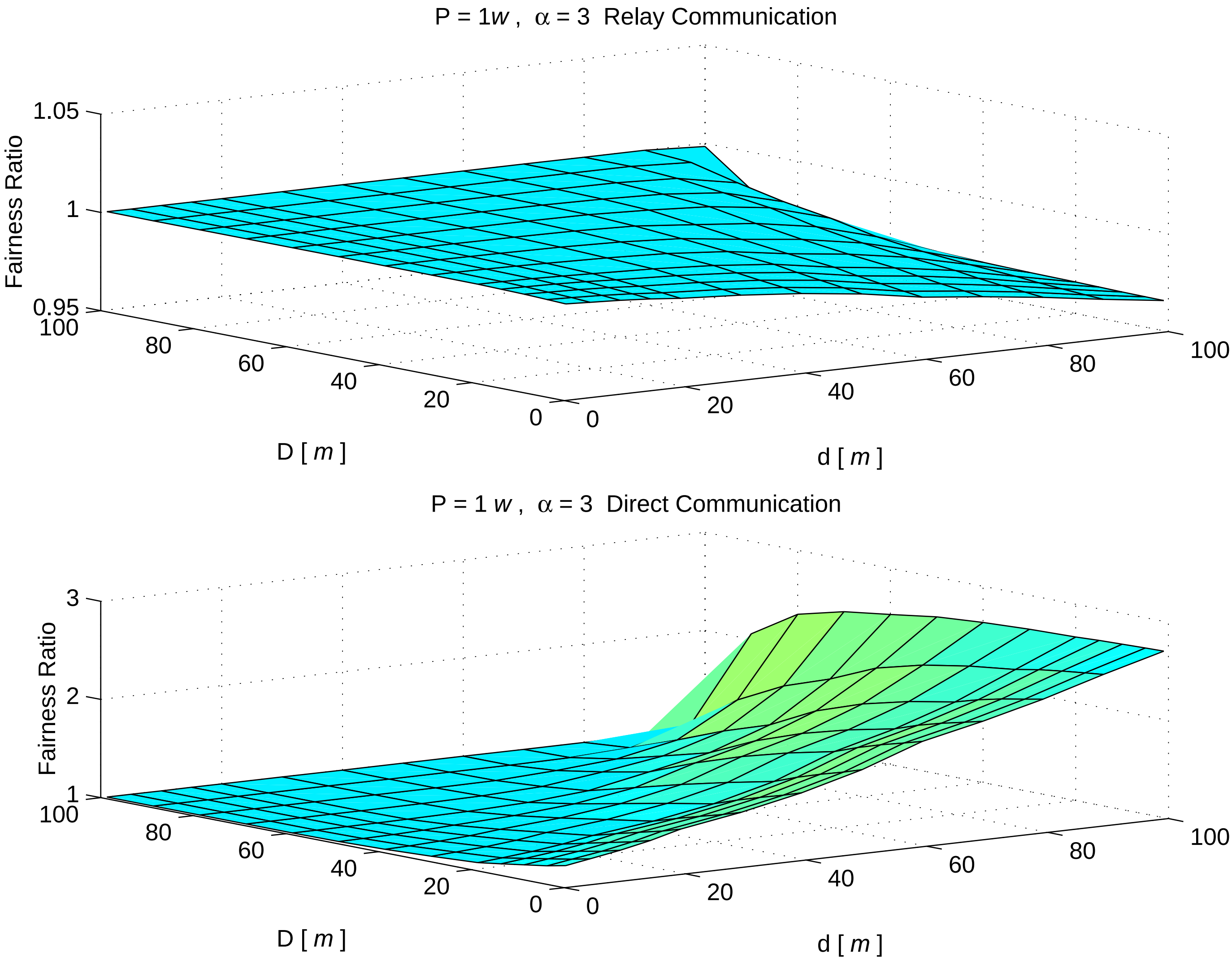

Figure 20: Comparison of the ratios of goodput of $M_2 \rightarrow M_1$ for direct and relay communication, $\alpha = 3$, $P_T = 1\text{W}$

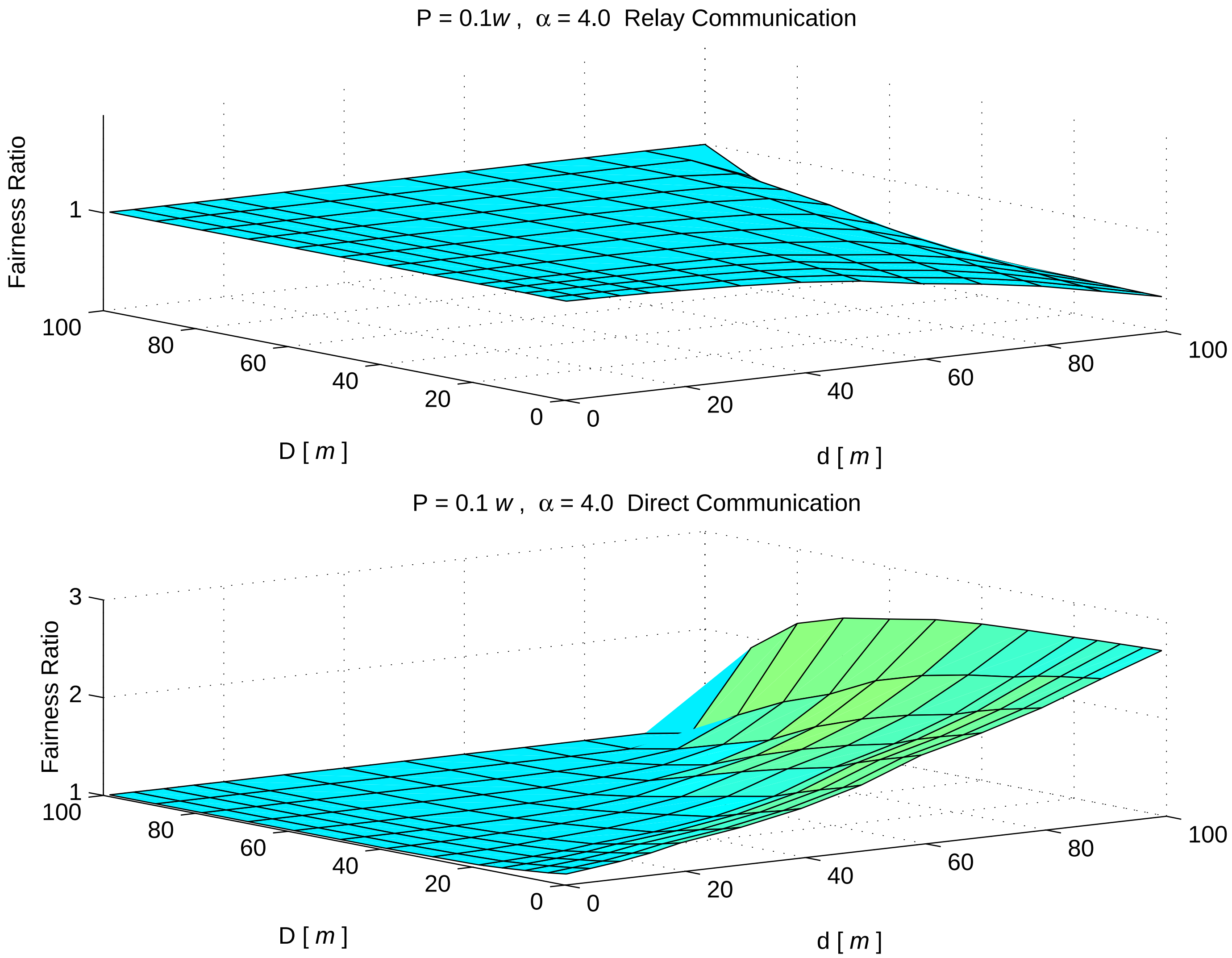

Figure 21: Comparison of the ratios of goodput of $M_2 \rightarrow M_1$ for direct and relay communication, $\alpha = 4$, $P_T = 0.1\text{W}$

6 Conclusions and Future Work

The analysis and numerical evaluations in Section 5 have shown that relaying can achieve considerably larger total goodput than direct communication in a TDMA-based wireless network. Critical parameters are the path loss coefficient α and the physical location of terminals. In this particular setup, best results were achieved when terminals were far away from their access points, yet the far terminals were still comparably close to each other. However, this means that the access points themselves were still separated by a considerable distance, as would be required be a spatial reuse scheme. Moreover, cells are not necessarily regularly shaped, and terminals can occasionally be far away from their access points, even more though as HiperLAN/2 is not primarily intended for usage scenarios where roaming/handover between different cells is always possible.

Regarding α, the larger it is, the more does relaying outperform direct communication. Best results shown here were achieved for $\alpha = 4$. In fact, values for α between 3 and 4 are commonly found in indoor environments (e.g., $\alpha = 3.8$ in a supermarket [3]), making relaying attractive for realistic scenarios. Even more important is the observation that already for α as small as 2.3 (lower values are rarely found in realistic scenarios), relaying never performs worse than direct communication.

And additional benefit of relaying communication is the better sharing of wireless capacity. The two stations of a cell receive a more equal share of the total bandwidth, with the far terminal slighly suffering compared to the direct case, but the inner terminal's share improving considerably and matching that of the far terminal. This effect is mainly due to the way transmission power has been chosen in this analysis, and more elaborate schemes to adjust this power for both the direct and the relay case are an important question for extending this work.

As this analysis only attempted to probe the potential of relaying in a very simple scenario, there are many ways to extend this work. One important extension is to consider larger scenarios, containing more terminals per cell and more cells, resulting in a higher amount of interference, which in turn should make relaying even more attractive. An additional question is whether and to what degree is it possible not to improve the goodput per terminal, but to add more terminals at the same quality of service.

However, as this will become more and more complex to analysis, we are currently developping a simulation environment to investigate both capacity and energy efficiency issues for relaying communication. This simulation will also take into account the impact of ARQ protocols, scheduling of communication to reduce delay when relaying, power adaptation schemes, and signaling overhead for protocols to determine terminals suitable for relaying. Also, as in larger configurations it might not be advisable to restrict a cell to the use of a single channel (relaying could happen in parallel within a cell if different channels are used), more elaborate physical channel model are necessary that include effects like adjacent channel interference. Also, more general mappings from interference/noise to packet error rates are required, as the numbers used in this paper, strictly speaking, only apply to the particular environment for which they were derived and can not be easily generalized.

Acknowledgements

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