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Capacity Increase of Multi-hop Cellular WLANs Exploiting Data Rate Adaptation and Frequency Recycling

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Abstract

The use of intermediate terminals for relaying traffic in infrastructure based wireless systems promises improvements in capacity, energy efficiency and coverage. This paper studies the possibility to increase capacity using intermediate mobile terminals as relayers, especially when using a second frequency to perform relaying in addition to a cell's primary frequency. This second frequency is obtained by "recycling" it from neighboring cells. These recycled frequencies are used at a reduced transmission power only in the interior of the cell, close to the access point. We show the trade-off between increased transmission parallelism in one cell and increased interference from other neighboring cells. We present algorithms that solve the two-frequency relaying problem, combining routing, scheduling and data rate adaptation while maintaining fairness in the system. For some combinations of primary and secondary frequency assignments ("macro" and "micro" frequency reuse patterns), we obtained up to 40% gain in capacity.

Keywords: Relaying, capacity, macro frequency and micro frequency reuse, WLAN, HiperLAN/2

Contents

Chapter 1

Introduction

In wireless communication systems, two communicating terminals can be too far apart to reasonably allow direct communication at high data rates. Reducing this distance by relaying between intermediate terminals can be beneficial regarding the total capacity, even in cellular-type networks—capacity here understood as the total amount of data transmitted by the access points(s) per unit time.

The intuition for increased capacity is that over shorter distances, faster data rates (due to adaptive modulation and coding) can be realized. As long as the data rates over a, say, two-hop route are more than twice as fast as over a direct communication, capacity increases (Section 3 shows an example). This argument, however, only holds if distances are actually reduced by relaying, i.e., if the relaying case is supposed to cover the same area as the direct communication case. Hence, we limit our attention to the application to relaying within existing cells; coverage extension is not the focus here.

Multi-hop communication provides an additional advantage over direct communication: There are more sender-receiver pairs than in the direct case, where the access point always participates and there is only a single pair. Hence, relaying offers the possibility to increase capacity even further by *concurrently* transmitting data, in multiple hops, towards the access point.

Scheduling such simultaneous transmissions within a cell on a single frequency, however, is hardly feasible due to then ensuing increased interference and packet error rate within a cell. But when using a second frequency, concurrent transmissions can proceed undisturbed, and a considerable gain in capacity can be reached [12].

A second frequency, however, is usually not easily available. When considering cellular systems, frequency reuse patterns are used (assuming some self-organization in the WLAN case for the moment). Hence, an additional frequency for one cell is only available by “recycling” it from a neighboring cell. Such recycling indeed has a viable chance to increase the overall system capacity, when looking at many cells: This second, recycled frequency could be used only in the interior of a cell, close to the access point, far away from the cell it originally belonged to, and used only at small transmission power. Consequently, there is a trade-off between the increased interference that this recycling will cause and the capacity gains within a cell that can be reached by two-frequency relaying.

Our contribution is to describe such a two-frequency relaying with frequency recycling. We distinguish two frequency reuse patterns: By *macro frequency* reuse pattern we refer to the standard, static frequency reuse pattern assigned to every AP in the network. The *micro frequency* reuse pattern is the one which determines how frequencies are recycled close to the AP for the sake of relaying. We will characterize their performance trade-offs and discuss frequency reuse patterns appropriate for two-frequency relaying.

The following Section 2 outlines our system model. Section 3 then describes how we combine data rate and transmission power adaptation, scheduling, routing, and frequency recycling to improve capacity in a wireless cell. The performance results of this scheme are given in Section 4, Section 5 puts our approach in perspective with related work. Finally, Section 6 concludes the paper.

Chapter 2

System model

As underlying technology, we use HiperLAN/2 [8] as a case study as it allows an easy control of relaying relationships and provides seven data rates (modulation plus coding rate) to choose from; additionally, it is quite amenable to a relaying extension in a cellular context [5]. In HiperLAN/2, the access point is responsible for computing a communication schedule for a MAC frame 2 ms long. In a frame, each mobile terminal is assigned time slots in which it is allowed to send or receive data to or from the access point or other mobile terminals. This schedule stipulates the transmission power and data rate used within a slot. Each slot transmits a data packet of constant size; the length of such a slot hence depends on the chosen data rate.

We use this system model to develop routing/scheduling algorithms for relaying that are based on estimates (provided e.g. by HiperLAN/2's "radio map") of the channel gains between terminals and access point. The access point only has information about terminals in its own cell and bases all its decision on this information. For simplicity, we assume that these estimates are known at the access point at no cost, that frequency switching times are negligible and that channels can be identified with distance.

Based on the channel gain, we compute the signal-to-noise ratio at a receiver for the performance evaluation: The noise is constant; the sender's transmission power can be obtained from the schedules and a simple pathloss model yields the received signal strength; doing that for all terminals (even outside a given cell) gives signal and interference power at a given receiver. Given the signal-to-noise ratio and the chosen data rate, the packet error rate (PER) for a data packet can be computed and packets are lost uniformly according to this rate. Details on the approximation of this error function can be found in [7, 8].

Chapter 3

Optimizing capacity

3.1 Example scenario

Consider a simple cellular network with three terminals A, B, and C as shown in Figure 3.1; assume that B is a potential relayer for A and C is communicating only directly with the AP. Evidently, A can improve its direct-communication capacity of 6 MBit/s to at least 9 (=18/2) MBit/s if the links A-B and B-AP are each used half the time that link A-AP would be used. Moreover, transmissions C's to AP and A's to B can concurrently be scheduled in two frequencies.

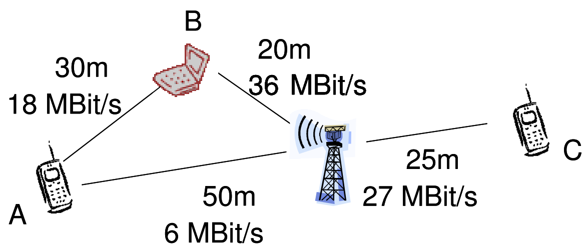

Figure 3.1: A simple cellular network scenario

Adding a second frequency for relaying could be seen as unfair: why not do so in the direct case as well and increase the bandwidth in the direct case correspondingly? But doubling the bandwidth can not be done with commodity radio equipment; relaying opens this possibility for flexible frequency use. In this sense, using a second frequency for relaying is essentially a legacy/cost and flexibility argument.

The question is then how to distribute frequencies to cells to maximally benefit from relaying. In this paper, the 3-, 7- and 19- macro and micro frequency reuse patterns are studied as shown in Figure 3.2.

Based on the macro frequency reuse pattern, every AP is assigned a frequency for its direct or one-frequency relaying communication. Even in two-frequency relaying, only the relay to AP communication is scheduled to another frequency while the rest continues to always use the primary frequency.

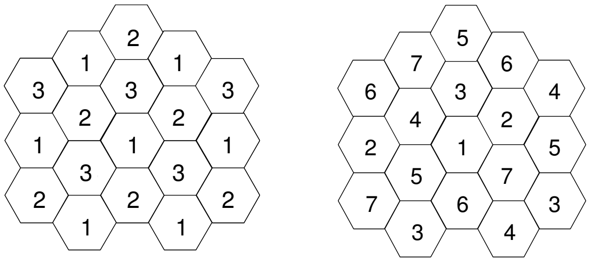

Figure 3.2: Macro frequency reuse pattern for 3 and 7 available frequencies

3.2 Routing and Rate Adaption

The potential benefit of relaying depends on the data rates that can be realized between relayed terminal, relaying terminal, and access point. Hence, a joint optimization of routing, data rate and power adaptation, and scheduling is necessary that decides which terminal to use for relaying and that selects modulation and transmission power. Currently, the algorithm optimizes only the uplink case and considers a single intermediate relay.

The effective data rate between any two terminals can be determined based on their distance and a target packet error rate which allows to compute, for each data rate, the required transmission power, using the (approximatively) known relationship between signal-to-noise and packet error rate is [8]. Any data rate that requires more than a maximum allowable power (here, 200 mW) or that does not match minimal required receiver sensitivity is ruled out. As a result, the optimal data rate for this pair of terminals is obtained. The smallest transmission power is used that still meets the target PER for this data rate. More details can be found in [12].

The routing then proceeds as follows: for a given time slot, a mobile terminal X calculates the effective data rate when sending its traffic directly to the access point. Terminal X then chooses an intermediate terminal and calculates the resulting effective data rate via this intermediary within the given time slot. If this effective data rate exceeds that of the direct transmission then the selected intermediate terminal is taken as a candidate relayer. Among the candidate relayers, the one with the largest throughput is finally selected as the relayer of terminal X. Otherwise X continues to communicate directly with the AP.

The routing decision takes place independent of interference as the AP has little or no knowledge about ongoing transmissions in other cells. Later on, when terminals sense the presence of interference, they readjust their data rate by first recalculating their actual PER. There can be situations where terminals can no longer transmit their traffic due to excessive interference. Such cases reduce the overall throughput considerably as they are already scheduled for communication.

3.3 Scheduling

Following the routing decision, terminals are then scheduled in the MAC frame depending on fairness considerations [12]. The simplest case, considered here, is that every terminal gets an equal time share of the entire frame. In direct communication, terminals are simply scheduled sequentially. For one-frequency relaying, the time slot of a relayed terminal is split into two: one sub slot is used for relayed to relaying terminal, the other sub slot for relaying terminal to AP communication.

For the two-frequency relaying case, there can be several alternatives for concurrent transmissions. The scheduler optimally selects the relay to AP communications and schedules them in the second frequency, in an overlapping time slot. If there are few pairs of independent communications, the two-frequency relaying schedule can degenerate to a one-frequency transmission schedule.

3.4 Frequency recycling

The second frequency comes from the micro frequency reuse scheme as shown in Figures 3.3a and 3.3b. The frequencies are recycled from neighbor's primary frequency and are used only close to the center of the cell. Moreover, the use of this second frequency is dictated by the scheduler, as long as there are independent entities for transmission. Since the communication distance is small, the transmission power is in turn small and hence the effect of this recycled freuency in terms of interference is not that severe on the neighboring cells. The relayed terminals, which are placed far away from the cell's center and responsible for most of the cell's interference, still use the cell's primary frequency according to the macro frequency reuse pattern.

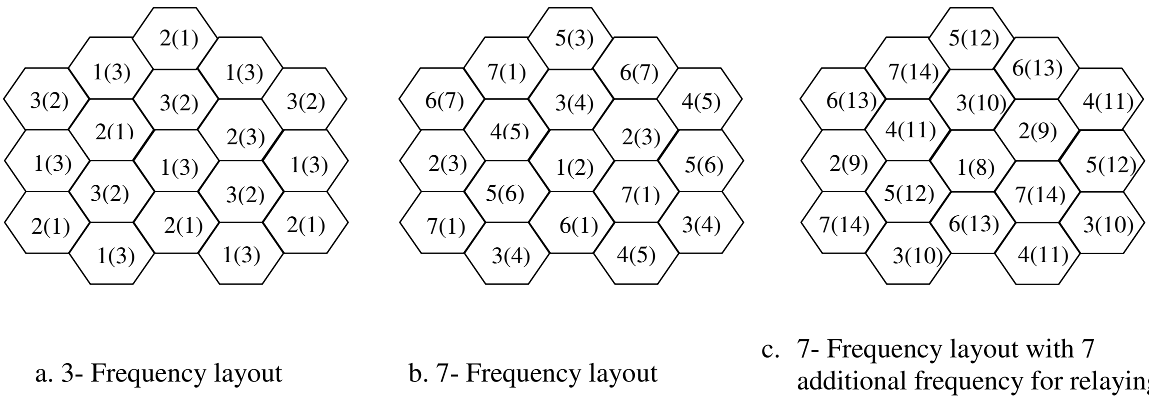

Figure 3.3: Macro and micro frequency reuse pattern for 3 and 7 available frequencies; secondary (micro reuse) frequencies are shown in parenthesis.

An alternative approach to frequency reuse is enabled by relaying when a large number of frequencies is available: instead of using, e.g., 19 frequencies to build a very wide-spaced macro frequency pattern, we can instead use these frequencies to enable two-frequency relaying based on a smaller macro reuse pattern. Thus, for the 7 macro frequency pattern, another micro frequency pattern is formed where every cell has a dedicated secondary frequency as in Figure 3.3c.

Chapter 4

Results

For the different frequency reuse patterns described, the throughput achieved by capacity-oriented schedules for direct communication, one-frequency and two-frequency relaying is evaluated by simulations. The average throughputof a cell is obtained with respect to a number of other cells, which are basically used as a source of interference and as a source of second frequency for relaying purposes. It is averaged over 55 different placements of terminals which are uniformly distributed within a hexagonal cell of radius 35m size, with the AP placed at the center.

Figure 4.1 shows the average throughput of a cell at the AP for a 7 frequency reuse pattern (the confidence interval is computed for 95% confidence level but it is not shown in the figures as it is small). The one-frequency relaying shows very little improvement in throughput over the direct communication, mainly because of the interference situation from the macro frequency reuse pattern. Since the reuse bandwith is limited to only 7 frequencies, the distance between two cells using the same (primary) frequency is also small, which makes the interference severe. When it comes to the two-frequency relaying case with recycled frequencies, the source of interference is both from the macro and micro frequency reuse pattern. However, since the communication distance is reduced by the relaying and since the micro frequency plan is used only close to the AP, the interference is reasonably reduced, increased parallelism outweighs the disadvantages, and hence there is upto 19% improvement in average throughput at the AP.

A similar situation is observed for a macro reuse pattern with 3 frequencies (not shown due to space limitations). As the frequency reuse distance is small, every transmission is vulnerable to severe co-channel interference. Though the micro frequency reuse scheme amends the situation to some extent, the overall throughput at the AP is considerably less than with 7 frequencies at hand. Nonetheless, when the available reuse frequencies are very few, relaying in two frequencies inevitably gives a better solution.

In the case of a 19 frequency reuse pattern, the interfering distance from co-channel cells is relatively large. As shown in Figure 4.2 the one-frequency relaying outperforms the direct communication, unlike the case of the 3 and 7 frequency reuse patterns. Upto 24% gain is also obtained when a micro-frequency plan with frequency recycling from neighboring cells is applied.

Comparing Figures 4.1 and 4.2 shows that the gain from adding 12 frequencies is actually small. Hence, these frequencies might perhaps be better used to support relaying. The interesting situation is when a 7 frequency pattern is used for the macro frequency reuse pattern and additional 7 frequencies (i.e. 14 frequencies in the system as a whole) are available for the micro reuse pattern as described in Section 3.4. As the recycled frequencies are not used from the immediate neighboring cells, the reuse

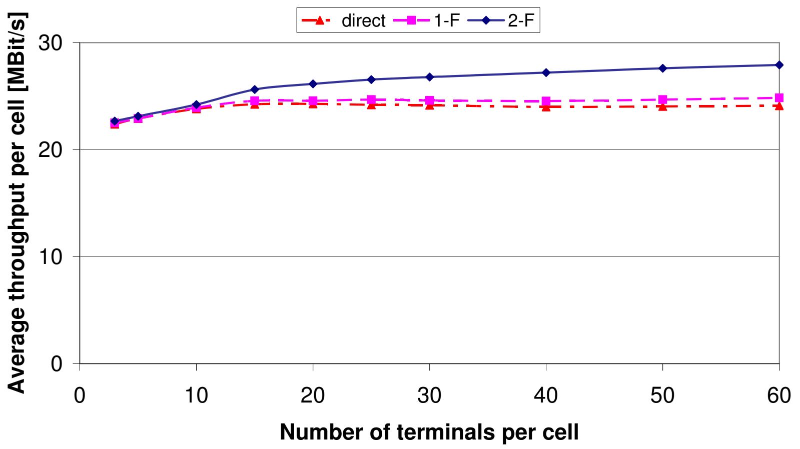

Figure 4.1: Average throughput as a function terminals per cell for 1% PER, $\alpha = 3.2$ and 7 frequency reuse pattern

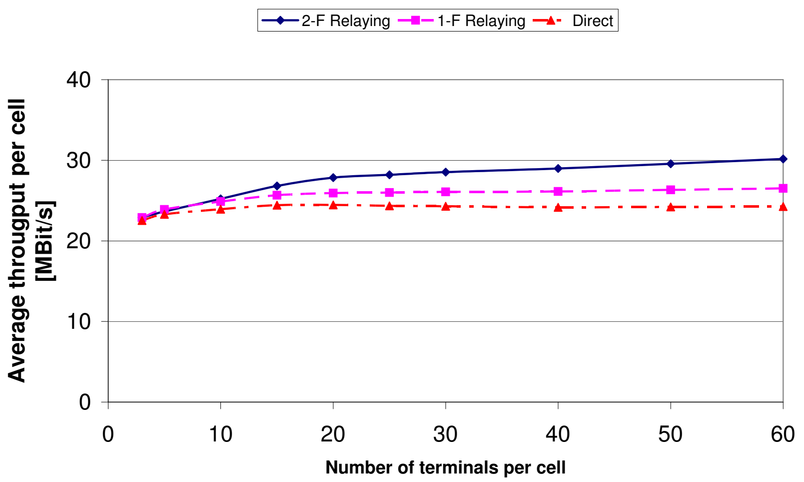

Figure 4.2: Average throughput as a function terminals per cell for 1% PER, $\alpha = 3.2$ and 19 frequency reuse pattern

distances are increased, which evidently bring about capacity improvement by reducing the level of interference. Figure 4.3 compares this situation with that of the 19 frequency reuse pattern. Upto 40% improvement can be obtained by the two-frequency relaying when the new micro frequency reuse pattern is used and yet 5 frequencies can be saved compared to the standard 19 frequency reuse pattern. This gives a good intuition to have a smaller frequency plan with a better figure of merit.

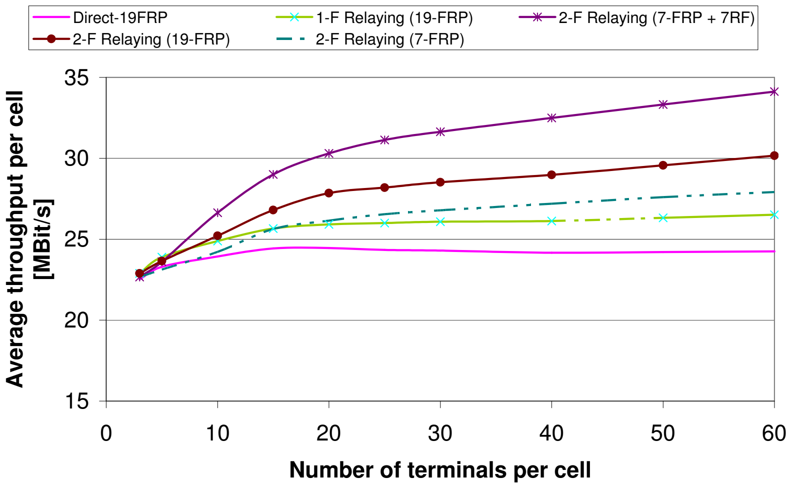

Figure 4.3: Comparison of average throughput as a function terminals per cell for 1% PER and $\alpha = 3.2$

Chapter 5

Related work

The notion of using relaying to improve capacity in wireless networks has been discussed in several contexts. GUPTA and KUMAR [3] have studied the capacity of randomly located ad hoc networks. Their result shows that for n identical, randomly located nodes, the maximum achievable 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. In their purely ad hoc network, they assumed that nodes can transmit at a given common channel and their results do not change if they subdivide the given channel. In our general model where nodes can communicate both with each other and with an AP, we also assumed a given channel at a system level but we subdivided it to reuse for both basic and relay transmissions. As a result, for a network with an increasing number of nodes we obtained a higher capacity upper bound due to frequency recycling than for a network without frequency recycling. Similar theoretical studies are also made in [2, 11].

Relaying in cellular and ad hoc systems has also been discussed by various authors. LIN and HSU [10] compared the end-to-end throughput of the conventional single-hop cellular network with that of a multihop cellular network architecture and by reducing the transmission distance within a cell, they demonstrated how multihop makes simultaneous transmissions possible so as to get improved throughput. But since packets are sent multiple times to arrive at destinations, the throughput achieved is limited due to bandwidth consumption. Our work is also based on the notion that terminals can communicate with each other for relaying purposes to open possibilities for simultaneous transmissions. Scheduling simultaneous transmissions in the same frequency within a cell without interference requires the cell to be large. Thus, we opted for additional relaying frequency for simultaneous transmissions to minimize interference within the cell. WU et al. [16] addressed the issue of increasing system throughput by introducing ad hoc relay stations in their integrated cellular and ad hoc relay (iCAR) architecture. These ad hoc relays are placed at strategic locations to divert traffic from heavily congested cells to other less congested cells. Such special devices are cost ineffective as they are fully utilized at times of heavy congestion only. But the relaying nodes in our cases are the terminals themselves with their own traffic to send to the AP and hence no additional device is required for the system.

The concept of channel reuse in relation to capacity of a cellular network has been studied by various authors [6, 9, 13, 15]. SRENG et al. [14] applied reuse of adjacent channels in relaying in TDMA cellular radio network, mainly to enhance coverage. They proposed a relay node selection scheme based on the pathlosses associated with two-hop relay links and relay channel selection schemes based on carrier-to-interference ratio received at the relay nodes from the channels to be reused. While the idea of relaying and adjacent channel reuse is similar, our approach is based on a joint routing and scheduling mechanism to optimize the capacity of the cellular network, by at the same time maintaining fairness in the system. We also have macro and micro frequency reuse pattern so as to use adjacent frequencies only close to the AP to minimize co-channel interference. Our routing mechanism is based on optimal data rate with power control which is adaptable in interference-limited environment.

Relaying in CDMA networks are studied in [1, 4]. HERHOLD et al. [4] showed how the overall performance of a CDMA relay system depends on the node density and the relative load and suggested that direct transmission eventually becomes favorable with respect to capacity consideration. In fact, our results also suggested that unless channel reuse is used, relaying in single frequency in interference-limited environment does not bring about a significant improvement in capacity.

Chapter 6

Conclusion and outlook

Relaying is a viable means to improve the operations of an infrastructure-based wireless communication system as it considerably increases the cell capacity. In this paper, we described two-frequency relaying algorithms which improve the system capacity and maintain fairness among terminals. The key technique is to recycle a frequency from a neighboring cell to use it in the interior of a cell to enhance transmission parallelism, hence improving capacity by keeping the access point busy at higher data rates — the disadvantages of higher interference are outweighed by the advantages. Alternatively, two-frequency relaying can be used, when many frequencies are available, to improve the overall frequency reuse pattern.

For some macro and micro frequency patterns, we obtained up to 40% gain in capacity in the network. Moreover, the algorithms are practical as they are not computationally intensive, they can be implemented as iterative online algorithms, and are based on information that can be provided by real systems with acceptable overhead. As no additional infrastructure is necessary and also the requirements on the individual terminals are quite modest, our relaying approach can provide a simple and cheap solution to add capacity to a wireless system, particularly in highly loaded networks. Currently, we are studying the impact of mobility and channel fading and the ensuing errors in channel gain estimates.

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