Chapter 1

FIXED RELAYS FOR NEXT GENERATION WIRELESS SYSTEMS

Concept, Protocol, Performance and Spectral Efficiency

Norbert Esseling, Bernhard H. Walke, Ralf Pabst
Chair of Communication Networks, Aachen University (RWTH), Kopernikusstrasse 16, 52074 Aachen, Germany

Abstract: This chapter presents a concept and the related performance evaluation for a wireless broadband system based on fixed relay stations acting as wireless bridges. The system is equally well-suited for both dense populated areas and wide-area coverage as an overlay to cellular radio systems. A short introduction is given to the general topic of fixed relaying. The proposed extension to a Medium Access Control-frame based access protocol like IEEE802.11e, 802.15.3, 802.16a and HIPERLAN2 is outlined. A possible deployment scenario is introduced and the simulative traffic performance in a Manhattan-like dense urban environment and a wide-area open-space environment is presented. It is established that the fixed relaying concept is well suited to substantially contribute to provide high capacity cellular broadband radio coverage in future (NG) cellular wireless broadband systems.

Key words: Fixed Relays; Multi-Hop; Hot-Area Scenario; Below Rooftop; Wide-Area Scenario; Above Rooftop; Wireless Broadband; Cellular Radio.

1. INTRODUCTION

Future broadband radio interface technologies and the related high multiplexing bit rates will dramatically increase the traffic capacity of a single Access Point (AP), so that it is deemed very unlikely that this traffic capacity will be entirely used up by the user terminals roaming in an APs service area. This observation will be stressed by the fact that future broadband radio interfaces will be characterised by a very limited range due to the very high operating frequencies (> 5 GHz) expected. Furthermore, future broadband radio systems will suffer from a high signal attenuation due to obstacles, leading either to an excessive amount of APs or to a high probability that substantial parts of the service area are shadowed from its AP. By means of traffic performance evaluation, this paper establishes that a system based on fixed mounted relay stations is well suited to overcome the problems mentioned. The paper is organised as follows. The introduction explains the advantages of relaying, presents fundamentals on how the proposed relaying concepts works in general and finally explains how to "misuse" existing standards to enable relaying in the time domain for wireless broadband systems based on a periodic Medium Access Control (MAC) frame, as used in IEEE802.11e, 802.15.3, 802.16a and HIPERLAN2 (H2). The latter system is taken to exemplify a detailed solution. Section 2 answers the question under what circumstances a relay based 2-hop transmission should be preferred to a 1-hop transmission between Mobile Terminal (MT) and AP. Section 3 presents the simulation environment, important parameters and the deployment scenarios used to obtain the performance results, which are given in Sections 4 and 5. Conclusions are drawn in Section 6.

1.1 Characteristics of the Relaying Concept

The properties of our relay concept and the benefits that can be expected are as follows:
Radio Coverage can be improved in scenarios with high shadowing (e.g. bad urban or indoor scenarios). This allows to significantly increase the Quality of Service (QoS) of users in areas heavily shadowed from an AP. **The extension of the radio range** of an AP by means of Fixed Relay Stations (FRSs) allows to operate much larger cells with broadband radio coverage than with a conventional one-hop system. The FRS concept provides the **possibility of installing temporary coverage** in areas where permanent coverage is not needed (e.g. construction sites, conference-/meeting-rooms) or where a **fast initial network roll-out** has to be performed. The wireless connection of the FRS to the fixed network **substantially reduces infrastructure costs**, which in most cases are the dominant part of the roll-out and operations costs. FRS only need mains supply. In cases where no mains is available, relays could rely on solar power supply. A **standard-conformant integration of the relays into any MAC frame based system** would allow for a **stepwise enhancement of the coverage region** of an already installed system. Investments in new APs can be saved and any hardware product complying to a wireless MAC frame based standard is possible to be used without modifications. The proposed relay concept can be recursively used to extend the radio coverage range of a single AP by multi-hop links.

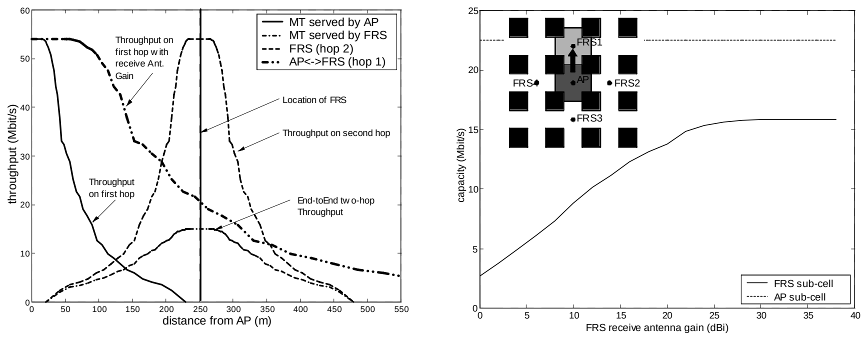

Figure 1-1. Left: Throughput for separate hops and end-to-end for MTs served by FRS (16dBi FRS receive antenna gain)
Right: Capacity of the AP in single-hop mode and capacity of a FRS

In this case, a FRS serves another FRS according to the needs besides serving the MTs roaming in its local environment. It is worth mentioning that we focus on relaying in layer 2 by means of what is called a bridge in Local Area Networks (LANs).

1.2 Fundamentals

In relay based systems, additional radio resources are needed on the different hops on the route between AP and MT, since multiple transmissions of the data have to take place. We have studied three concepts and present here the results of the first one.

Relaying in the Time-Domain: The same frequency channel is used on both sides of the relay. A certain part of the MAC-frame capacity is dedicated to connect MT and FRS and the rest is used to connect AP and FRS via a time-multiplexing channel. One transceiver only is needed in a FRS, which results in cheap, small and energy-efficient FRSs. The physical layers of the standard air interfaces considered do not require any modifications. Instead the FRS concept is realised throgh the MAC protocol software only.

Relaying in the Frequency-Domain: This concept uses different carrier frequencies on links a FRS is connecting. The two hops can be operated independently of each other at the cost of increased complexity of the hardware and the frequency management.

Hybrid Time-/Frequency-Domain Relaying: In the hybrid concept[1], the FRS periodically switches between two frequencies, allowing the AP to continue using its frequency f_1 while the relay serves its terminals on frequency f_2. No additional transceiver is needed, but the hardware complexity is increased since a very fast frequency switching has to be supported.

We will focus on the time domain relaying in this paper. To illustrate the capabilities and properties of relaying in the time domain, results of a model based analysis of the throughput over distance of a MT from the AP and of the achievable capacity for the scenarios shown in Figure 1-8 are presented.

Based on the relation shown in Figure 1-5 for an 802.11a modem and an analytical calculation of the $C/(I+N)$ expected at certain distances from the AP and/or FRS, we obtain a relation between the packet error rate (PER) and distance of the MT from the AP/FRS. Assuming an ideal Selective Reject-Automatic Repeat Request (SREJ-ARQ) protocol, we have calculated the resulting relation between throughput and distance from the AP/FRS, see the solid curve in Figure 1-1 (left). We assume further that the FRSs have directive transmit/receive antennas to communicate with the AP and an omnidirectional antenna to communicate with MTs. Gain antennas at the FRS result in an improved throughput-distance relation between AP and FRS, as is visible from the dotted curve in Figure 1-1 (left). The throughput of a MT that is served by the FRS (dashed curve in Figure 1-1, left) in general obeys the same throughput-distance relationship that is also valid for MTs served by the AP directly. The dash-dotted curve finally denotes the maximum achievable two-hop throughput of a MT served by the FRS. It is clearly visible that a considerable extension of the radio coverage range can be achieved through the use of the relay station with a 16 dBi gain antenna assumed. Figure 1-1 (right) gives the capacity of the AP sub-cell (horizontal line) and compares that with the FRS sub-cell capacity for the case that the whole AP capacity of the 2-Hop-Cell is made available only to one single FRS with varying FRS receive antenna gain. “Capacity” denotes the achievable aggregate cell throughput under the assumption of uniformly distributed MTs generating a constant bitrate type load[2]. The capacity of the AP (this case is equivalent to the AP operated as a conventional BS) amounts to 22.51 Mbits. The capacity that can be made available at the FRS, i.e., when the whole capacity of the AP is transferred to the area that is covered by one of the FRSs, amounts, depending on the FRS receive antenna gain, to values between 2.7 Mbits for 0 dBi gain and 15.87 Mbits for 30 dBi gain. The gap between the two curves in Figure 1-1 (right) denotes the capacity that has to be invested into the extension of the coverage range by means of relaying.

1.3 Realisation of MAC frame based Relaying - Example: HIPERLAN2

The HIPERLAN2 (H2) system is used here as an example to explain how MAC frame based protocols as 802.11e, 802.16a (HIPERMAN) and the recently adopted 802.15.3 can be applied to realise relaying in the time domain. All the MAC and PHY functions addressed here are existent in all these wireless standards and no changes of the existent specifications are needed for relaying. However, either the Logical Link Control (LLC) or MAC layer now needs a store-and-forward function like that known from a bridge to connect LANs to each other. In the description of a H2 relay we also use the term Forwarding when referring to Relaying. H2 specifies a periodic MAC frame structure, Figure 1-2. In the Forwarding Mode (FM) both signaling and user data are being forwarded by the FRS. An FRS operating in FM appears like a directly served MT to the AP. **Therefore, this does not preclude the possibility of allowing any MT to act as relay to become a Mobile Relay Station (MRS).** MTs are referred to as Remote MTs ((R)MTs) if they are served by a FRS.

The capacity of the MAC frame (see Figure 1-2, upper part) is assigned dynamically in a two-stage process[3].

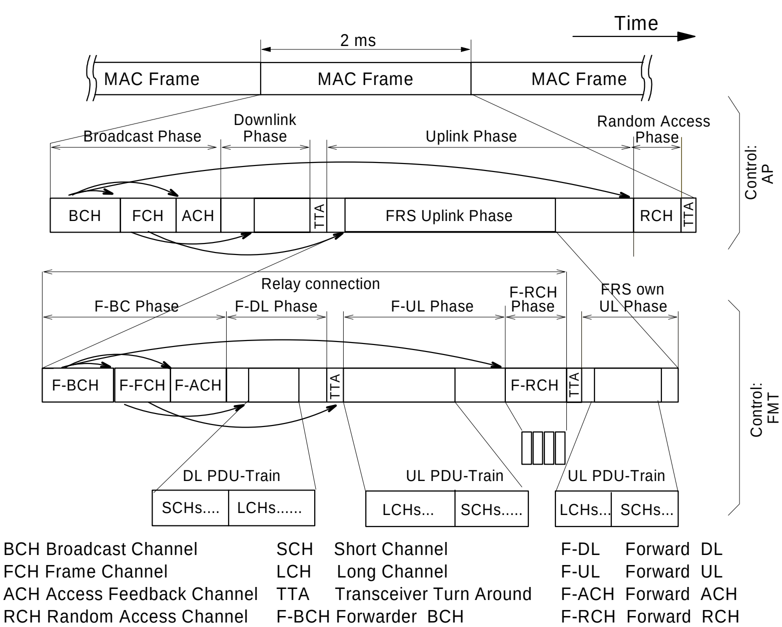

Figure 1-2. Standard-conformant enhancements of the H2 MAC frame

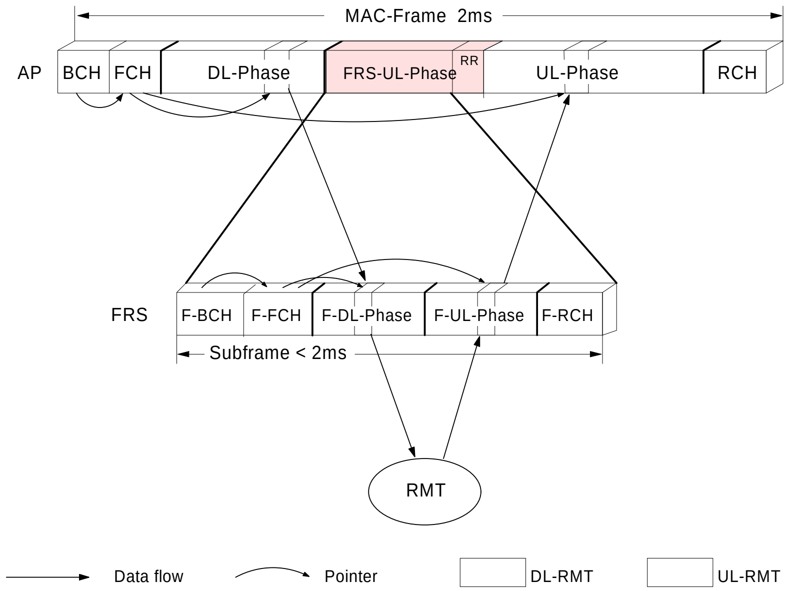

Figure 1-3. Data flow using a sub-frame in 2-Hop mode

Transmit capacity for terminals directly associated to the AP (FRSs and MTs) is allocated by the AP. An FRS appears to the AP like a MT but sets up a Sub Frame (SF) structure, which is embedded into the H2 MAC frame structure of the serving AP (refer to Figure 1-2, bottom).The SF structure has available only the capacity assigned by the AP to the FRS.

This capacity is dynamically allocated by the FRS to its RMTs according to the rules of the H2 MAC protocol. Using this scheme, the FRS needs one transceiver only. The SF is generated and controlled by the FRS (shown in Figure 1-3) and it is structured the same as the MAC frame used at the AP. It enables communication with legacy H2 terminals without any modifications. It implements the same physical channels as the standard H2 (F-BCH, F-FCH, F-ACH, F-DL, F-UL and F-RCH), which carry now the prefix "F-" to indicate that thy are set up by the FRS. A RMT may also set up a SF to recursively apply this relaying concept in order to cascade multiple relays.

Figure 1-2 shows the functions introduced to the H2 MAC frame to enable relaying in the time domain. The capacity assigned in the MAC frame to the FRS to be used there to establish a SF is placed in the UL frame part of the AP. When the FRS is transmitting downlink, the data is addressed properly to its RMT and the AP will discard this data accordingly. The same applies for data transmitted from the RMT to the FRS. The capacity to exchange the data between AP and FRS has to be reserved as usual in both UL and DL directions on request by the FRS[3]. A very similar operation is possible by using the Hybrid Coordinator Access in IEEE802.11e[4].

2. ARQ-THROUGHPUT 1-HOP VS. 2-HOP

The question arises under what circumstances relaying would be beneficial, i.e. when a 2-hop communication is preferential to one hop. Figure 1-4 shows analytical results[5] comparing the throughput achieved with 1-hop and 2-hop transmission for the two scenarios depicted in the upper right corner of the figure under Line of Sight (LOS) radio propagation.

It is assumed that the FRS is placed at half the distance between the AP and the (R)MT. It turns out that from a distance of 370 m onwards, the 2-hop communication delivers a somewhat higher throughput than 1-hop, as marked by the shaded area.

Relay based 2-hop communication provides another considerable benefit already mentioned in Section 1.1: it is able to eliminate the shadowing caused by buildings and other obstacles that obstruct the radio path from an AP. An example of this is given by the scenario in Figure 1-4 together with the throughput gain (shaded) resulting from relaying.

In this scenario, the AP and the (R)MT are shadowed from each other by two walls that form a rectangular corner, e.g. a street corner. The COST259 propagation model (see Section 3.3) was used and the walls were assumed to have an attenuation of 11,8 dB each. The shaded area highlights that the 2-hop communication gains over one hop, starting at a distance of 30 m only.

The two examples establish that relaying is of advantage for both, increasing the throughput close to the cell border of an AP (under LOS conditions) and for bringing radio coverage (and throughput) to otherwise shadowed areas.

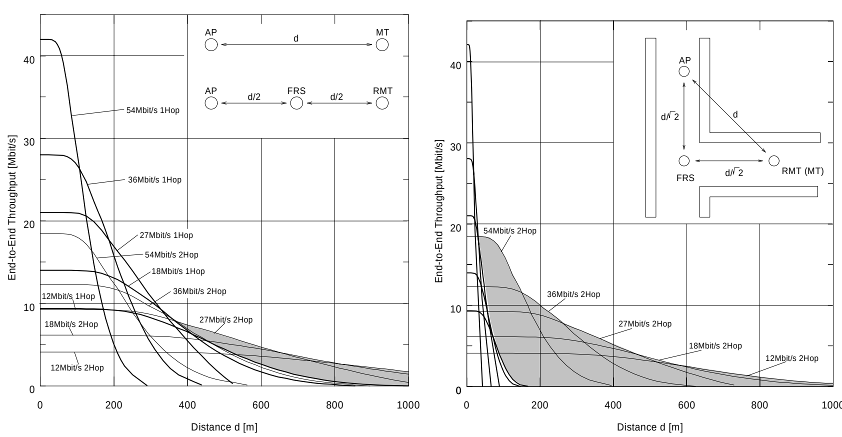

Figure 1-4. Comparison of the maximum achievable End-to-End Throughput over Distance for a 1- and 2-Hop Connection with ARQ

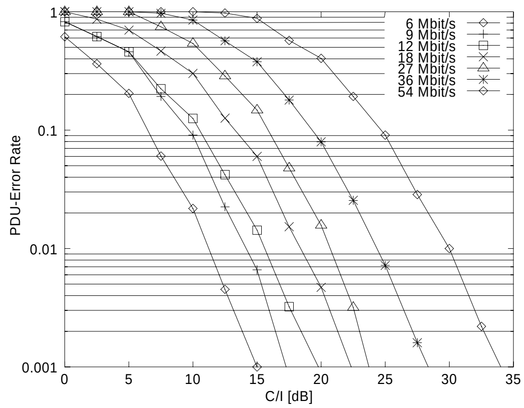

Figure 1-5. PDU-Error Probability for varying C/(I + N) and PHY-mode[8]

It has been explained by means of Figure 1-1 that relaying is consuming part of the capacity of an AP, since the relayed data has to go twice over the radio channel. It has been shown[6] that for relay based deployment concepts (like the one shown in Figure 1-6, left) MTs served at different relays that belong to the same AP can be served at the same time, whereby the capacity loss introduced by 2-hop communications can be compensated to a great extent.This capacity loss can even be turned into a substantial gain, if directive antennas are used at FRS as is shown in Section 4. Even if there is still a capacity loss resulting from a relay based system, this concept is able to trade the capacity available at an AP against range of radio coverage[7].

The trend towards increasing transmission rates resulting from further developed radio modems tends to provide an over capacity in the cell area served by an AP, especially in the first months/years after deploying a system. Relays substantially increase the size of the service area thereby increasing the probability that the capacity of an AP will be used effectively.

The next sections present a simulation-based performance evaluation of a relay-based system in a Manhattan-type environment.

3. SCENARIO AND SIMULATION ENVIRONMENT

3.1 Scenario: Dense Urban Hot Area Coverage

The dense urban environment with a high degree of shadowing has been identified as a scenario especially suited for deploying a relay based wireless broadband network. The Manhattan grid scenario[9] has been taken for the following investigations, see Figure 1-6. The most important parameters of the scenario are the block size of 200 m and the street width of 30 m. In the deployment scenarios without relays shown in Figure 1-7, each of the APs covers the range of two building blocks and one street crossing, resulting 430 m range.

This cell configuration requires a minimum of 4 carrier frequencies to ensure that in each direction, the co-channel cells are separated by at least one cell with another carrier frequency, see Figure 1-7 (left). Based on that structure, two possible variants can be considered. The APs can be placed at equal coordinates in adjacent streets, shadowed by the buildings (Figure 1-7, middle). The second variant is that APs are placed on street crossings (Figure 1-7, right), thereby covering horizontal and vertical streets. In this scenario without using relays, at least 8 frequencies are needed to ensure that co-channel cells are separated by cells using a different frequency.

All three scenarios shown in Figure 1-7 require that a cellular coverage in the Manhattan scenario would have to rely on LOS, leading to a high number of APs. Besides covering the scenario area with a single hop system, we study the impact of covering the the same area with a system based on relaying. The basic building block, which consists of an AP and 4 FRSs is shown in Figure 1-6 (left). It has the potential to cover a much larger area than one Single-Hop AP. Figure 1-8 (top) shows the cellular deployment of these building blocks for various cluster sizes. Owing to the high attenuation caused by the buildings, only those co-channel interferers have to be taken into account that are marked in the figure in black and the reuse distance is indicated by the black arrows. For the cluster sizes N=2/3/4 we obtain reuse distances D=1380 m/2070 m/2760 m.

3.2 Scenario: Wide Area Coverage

The low coverage range that wireless broadband systems exhibit at high bitrates is shown in Figure 1-4 (left). In a conventional 1-hop hexagonal cellular approach, this leads to a large number of APs required for continuous coverage. It has already been suggested that the use of fixed relays can help to increase broadband radio coverage and thus reduce the number of APs needed. Figure 1-6 (right) shows the basic element (further referred to as "cell") used to achieve wide-area-coverage in a cellular approach. It consists of an AP and 3 surrounding FRSs which can be embedded into a hexagonal cell structure. We consider a coverage radius for a single AP or FRS of R=200 m. The result is that a relay based cell, which consists of 4 sub-cells has a radius of R=346 m. According to Figure 1-8 (bottom), different cluster sizes (N=3,7,12) can be realized just like in a traditional hexagonal cellular approach.

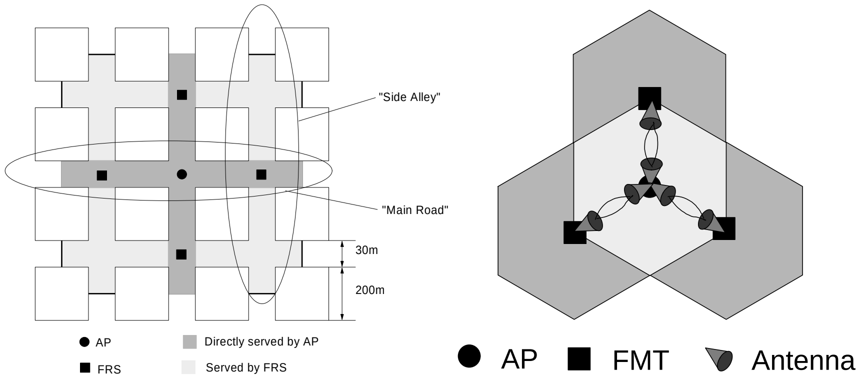

Figure 1-6. Left: Relay-based cell with four relays (below rooftop) in the Manhattan scenario Right: Relay-based cell with three relays (above rooftop) in a wide-area scenario

3.3 Air Interface

All of the MAC frame based air interfaces mentioned above will operate in the 5 GHz licence-exempt bands (300 MHz in the US, 550 MHz in Europe, 100 MHz in Japan). We assume for the following studies that the physical layer (PHY) uses an OFDM based transmission with 20 MHz carrier bandwidth subdivided into orthogonal sub-carriers. The modem is assumed conformant to the IEEE802.11a standard. As indicated in Section 1, the 5 GHz frequency range is characterised by high attenuation and very low diffraction, leading to low radio range, which is one of the key problems addressed by the proposed relaying concept.

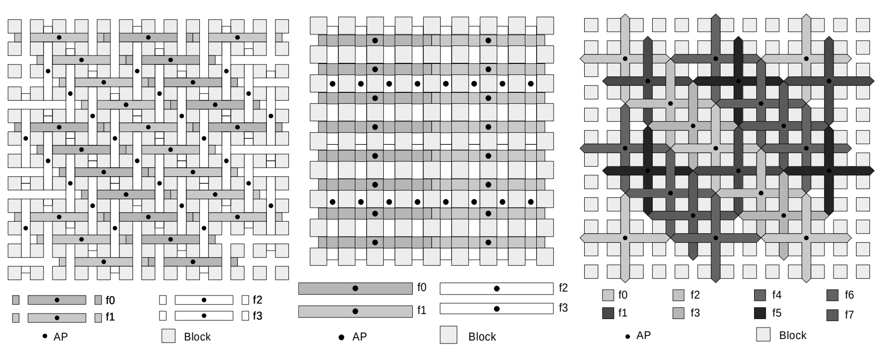

Figure 1-7. Possible AP deployments without relays

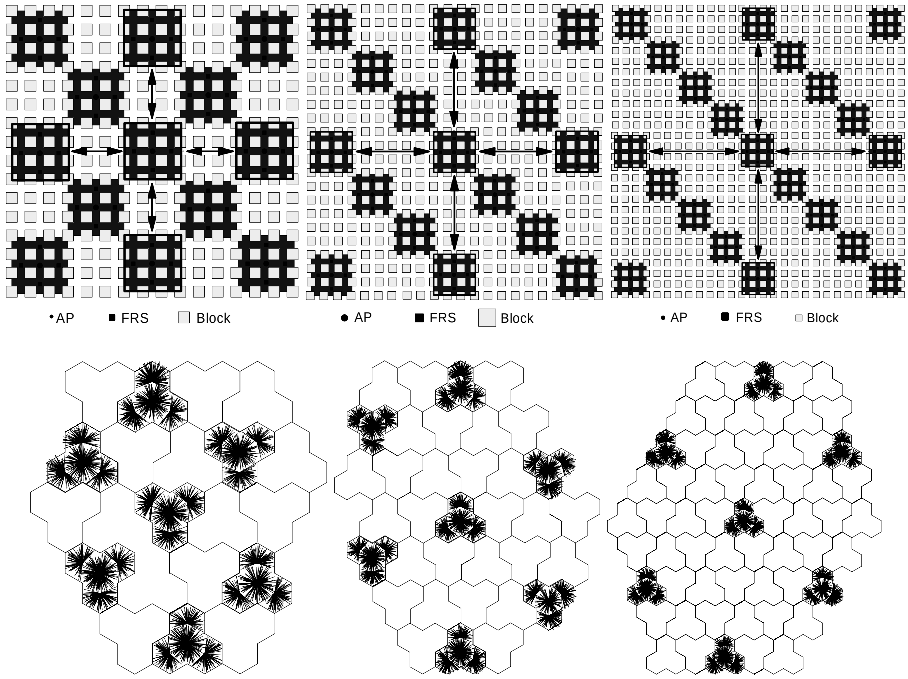

Figure 1-8. Top: City-wide coverage with relay-based cells for different clustersizes N=2,3,4 Bottom: Wide-area coverage with relay-based cells for different clustersizes N=3,7,12

Link-Level Performance: The basis for the calculation of the transmission errors is the ratio of Carrier to Interference and Noise power (C/(I+N)). The results of Link-level investigations[8] provide a Protocol Data Unit (PDU) error-probability related to the average C/(I+N) during reception of the PHY-PDU. This relation is shown in Figure 1-5. In our simulation model, collisions of interfering transmissions are detected and the resulting average C/(I+N) is calculated for each transmitted PHY-PDU to decide on success or retransmission.

Propagation Models: The COST259 Multi-Wall model has been used in the Manhattan scenario. This model[10] is an indoor propagation model at 5GHz, which takes into account the transmission through walls obstructing the LOS between transmitter and receiver. Unlike in the COST231 model[11], the attenuation non-linearly increases with the number of transmitted walls. Wall attenuations have been chosen according to the suggestions from the BRAIN project[12].

The Propagation Model used in the wide-area simulations is the Large-Open-Space model[9] and a pathloss exponent of γ=2,5 has been used.

Other Parameters of the Simulation Model: To determine whether a MT should be served by the AP directly or via a FRS, the path loss between

AP and MT is assessed. If it is higher than a certain threshold, the MT is associated to the closest available FRS ("closest" in terms of pathloss). The traffic load is assumed to be constant bitrate, which is a reasonable assumption when investigating the maximum achievable end-to-end throughput.

4. SIMULATION RESULTS

This section presents the performance evaluation results obtained by stochastic-event driven simulation. Results for the Downlink (DL) direction are presented here only, since the main effects that can be observed are quite similar in Uplink (UL) and DL directions, a result which is partly due to the Time Division Duplex air interface studied. We have also performed a mathematical analysis of the scenarios and the results validate the simulation results as visible from the results figures. This work will be published in the near future.

4.1 Reference Scenarios without Relays

In Figure 1-9 (left) the DL C/(I+N) and the related maximum End-to-End throughput are plotted over the distance of the MT from the AP when servicing the scenario by APs only, according to the Manhattan and the Wide-Area scenarios.

In the Manhattan Scenario, the C/(I+N) values are slightly higher for the deployment variant where the APs are placed on the street crossings (Figure 1-7, right) when compared to the other options. Figure 1-9 (upper right) shows the resulting Throughput (TP), again versus the distance of the MT from the AP. At distances of 115 m and 345 m, some additional interference on the crossings is visible for a deployment according to Figure 1-7 (right)

In the wide-area cellular deployment, the C/(I+N) values degrade as expected with decreasing cluster size. For comparison, also the C/(I+N) for a single AP without Interference is shown. Figure 1-9 (lower right) shows that at the cell border (at a distance of 200 m), a maximum End-to-End throughput of ca. 8 Mbit/s can be provided in the very optimistic case of N=19.

4.2 Simulation Results with Fixed Relay Stations: Manhattan Scenario

Simulations with fixed relays as introduced in Section 3.1 have been performed for the cluster sizes N=2/3/4, cf. Figure 1-8. Figure 1-10 (left) shows two sets of curves in one graph:

The C/(I+N) versus the distance of a MT from the AP (marked with 1. hop) and the C/(I+N) encountered by MTs being served by a FRS (marked with 2. hop). The FRS is located at a distance of 230 m from the AP on the "Main Road" (cf. the pictogram in the figure and Figure 1-6). This explains the peak of the C/(I+N) curve visible at that distance. Each set of curves has the cluster size N as a parameter. As expected, the curves with N=2 show the lowest C/(I+N) values. Figure 1-10 (right) shows the C/(I+N) situation in the "Side Alley" of the relay based cell. Like on the first hop, the situation for the MTs is almost similar to that of the MTs served directly by the AP in the single hop case, with the difference that the next LOS co-channel interferer is more than 780 m away, leading to lower interference and thus to a C/(I+N) which is approx. 4 dB higher than in the single hop case.

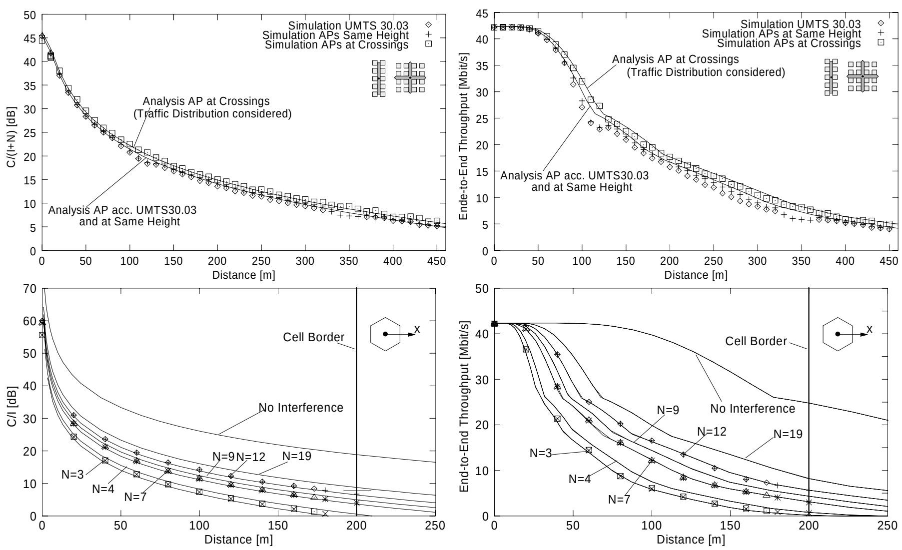

Figure 1-9. Top: C/(I+N) (left) and End-to-End-Throughput (right) without relays in Manhattan Scenario (Lines: analysis, Markers: simulation)
Bottom: C/(I+N) (left) and End-to-End-Throughput (right) without relays in wide-area scenario (Lines: analysis, Markers: simulation)

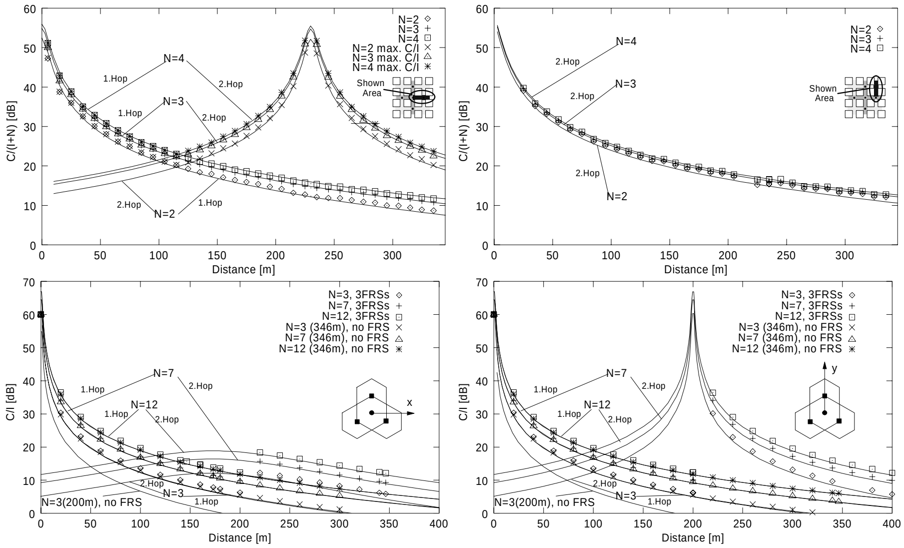

Figure 1-10. Top: DL C/(I+N) vs. Distance from (R)MT to AP respectively FRS for varying cluster sizes (2, 3, 4) using relays (Left: “Main Road”, Right: “Side Alley”, Lines: analysis, Markers: simulation)
Bottom: Top: DL C/(I+N) vs. Distance from (R)MT to AP respectively FRS for varying cluster sizes (3,7,12) using relays (Left: “x-axis”, Right: “y-axis”, Lines: analysis, Markers: simulation)

A maximum TP of approx. 4-5,5 Mbit/s (depending on N) can be made available even at the cell border of the second hop, in an area which has no direct coverage of the first hop at all and which would require an additional AP in a single hop scenario (see Figure 1-7, right). Figure 1-10 (upper left and right) shows the resulting 2-hop TP for MTs on the "Main Road" and the "Side Alley" respectively with omnidirectional antennas used at AP, FRS and MTs. Obviously, the TP on both the first and the second hop depends on the cluster size N.

The relatively flat slope of the curves for the second hop indicates that the TP is upper-bounded by the capacity available at the FRS from the AP. More capacity can be provided when using gain antennas at FRSs and omni antennas at AP and MT, with the FRS serving its MTs with an omni antenna. The improvement in TP for the outer range of the relay based cell with an 11,8 dB gain at the FRS can be seen when comparing the left and right hand graphs in Figure 1-11. As predicted in Figure 1-1 (right), the resulting higher TP on the first hop allows a FRS to have much more capacity available in its service area.

At a gain of 11,8 dB, which is an intermediate value according to Figure 1-1 (right), an increase in max. TP of up to 80% (from 8 Mbit/s to 14 Mbit/s) can be observed on the second hop, both on the "Main Road" and in the "Side Alley".

4.3 Simulation Results with Fixed Relay Stations: Wide-Area Scenario

Simulations with fixed relays have also been performed in a wide-area above-rooftop deployment for the cluster sizes *N*=3/7/12, cf. Figure 1-8 (bottom). Figure 1-10 (bottom left and right) shows the C/(I+N) over distance of the MT from the AP respectively the FRS. The FRS is located at a distance of 200m from the AP along the y-axis (see pictogram). This explains the characteristic peak of the curves denoted "2. Hop". It is further visible in both sub-figures that the impact of the cluster-size on the expected C/(I+N) values is considerable. For reference, the figures also show the C/(I+N) curve for the N=3 and R=200 m one-hop scenario. It shows that the relay deployment helps to considerably improve the C/(I+N) values. The left-hand side of Figure 1-12 shows the maximum achievable Downlink End-to-End throughput versus the distance (in x- and y-direction) of a MT from the AP (marked with 1. Hop) and the throughput encountered by MTs being served by a FRS (marked with 2. Hop).

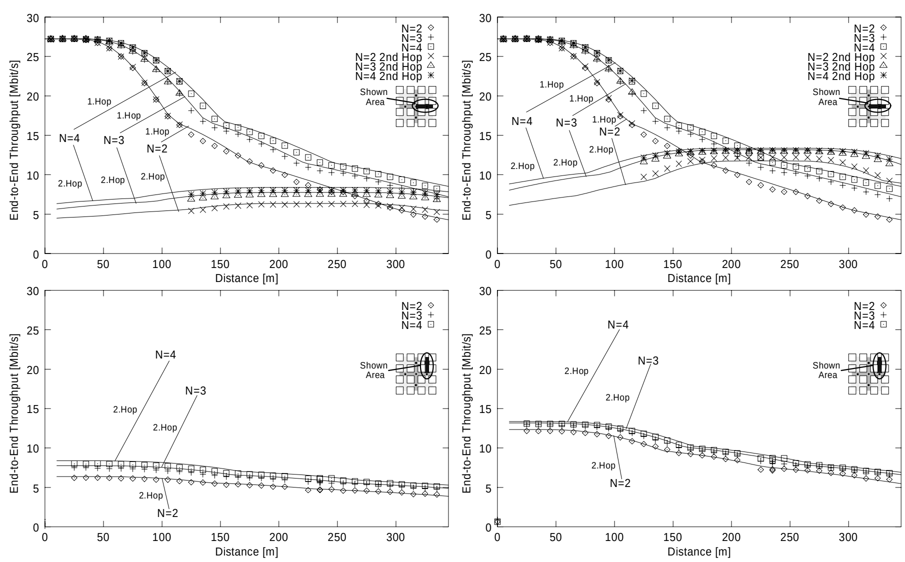

Figure 1-11. DL End-to-End-Throughput vs. Distance from (R)MT to AP respectively FRS for varying cluster sizes (2, 3, 4) using relays (left: using omni antennas only, right: with 11,8 dB receive antenna gain at the FRS (Lines: analysis, Markers: simulation)

The FRS are located at a distance of 200 m from the AP, e.g. in the y-direction (shown in the pictogram). This explains the maximum of the throughput curve for the second hop visible at that distance. Each set of curves has the cluster size *N* as a parameter. As expected, the curves with N=3 show the lowest throughput values, owing to the highest encountered interference. The right-hand side of Figure 1-12 shows the maximum achievable Downlink End-to-End throughput when an antenna gain of 11,8 dB is assumed between AP and FRS. Again, the upper figure represents the situation along the x-axis, while the lower figure refers to the y-axis of the relay based cell (also refer to the small pictograms included).

Like on the first hop, the situation for the MTs is almost similar to that of the MTs served directly by the AP in the single hop case (included for reference with a cell size of R=346 m).Depending on the cluster-size, the maximum End-to-End throughput along the y-axis improves for ranges greater than 220 m (N=3), 280 m (N=7) and 320 m (N=12) when relay stations are used instead of a single hop deployment. Along the x-axis improvements can be observed for N=3 and N=7 (ranges > 250 m and 325 m). In Section 2 we additionally show the result for the case where no co-channel interferers are present. In that case, improvements of the maximum throughput can be observed for distances greater than 370 m.

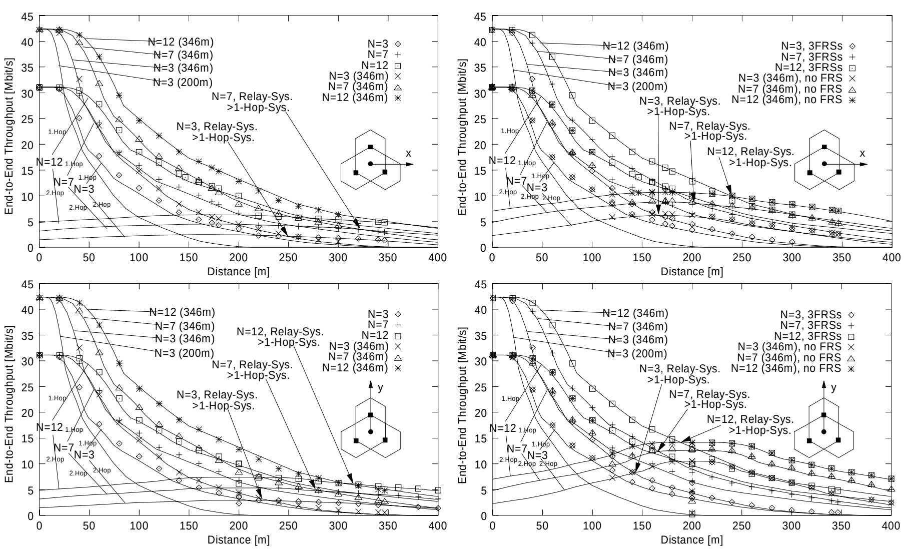

Figure 1-12. Maximum DL End-to-End-throughput vs. Distance from (R)MT to AP respectively FRS for varying cluster sizes (3, 7, 12) and sub-cell radii (200 m, 346 m) using relays (left: using omni antennas only, right: with 11,8 dB antenna gain between AP and FRS (Top: “x-axis”, Bottom: “y-axis”, Lines: analysis, Markers: simulation)

If an additional antenna gain is assumed between AP and FRS, the advantages of the FRS concept can already be observed at about 140 m (N=3), 170 m (N=7) and 190 m (N=12) along the y-axis, while - along the x-axis - the throughput of the two hop system outperforms the one-hop system starting at 170 m (N=3), 200 m (N=7) and 240 m (N=12). In general, a considerable improvement compared to the deployment without gain antennas can be observed. In addition, a more homogeneous distribution of the maximum achievable throughput can be noticed, which is especially beneficial in areas close to the cell border. The tighter the frequency reuse, the smaller becomes the minimal range where the use of FRSs is beneficial. Also, the number of necessary frequency channels is reduced with lower cluster sizes. This allows to use more frequency channels per cell and thus to increase an operators network capacity. When using FRSs, even in a cluster with N=3 the cell border can be served at sufficient quality due to the range extension. The gain obtained from the relaying scheme justifies transmitting the information twice.

The results given above are for the comparison of one- and two-hop cells with the same cell area (equal AP density). If an N=3-cluster with 200 m-cells is compared with a N=3 relay cell with 200 m sub-cells (equal site density), the advantages of the relay-based concept already become visible at distances > 30 m from the AP.

Table 1-1. Average Cell Capacity and spectral efficiency for a Cell with 10 MTs and Exhaustive Round Robin (ERR) Scheduling, comparing three Manhattan Single-Hop deployments with Multi-Hop deployment (with and without Receive Antenna Gain at the FRSs)

Scenario	Used # of Freq.	Cell Size $[m^2] / 10^3$	Cell Capacity [Mbit/s]	Spect. Efficiency $[\text{bit s}^{-1}\ \text{Hz}^{-1}\ \text{m}^{-2}]$
1-Hop (UMTS 30.03)	4	25,8	21,04	10,19
1-Hop (horiz./vert. depl.)	4	25,8	20,01	9,69
1-Hop (APs on cross.)	8	53,4	20,24	2,37
2-Hop N=2	2	116,0	7,26	1,56
2-Hop N=3	3	116,0	9,03	1,30
2-Hop N=4	4	116,0	9,80	1,06
2-Hop N=2, +11,8 dB	2	116,0	10,72	2,31
2-Hop N=3, +11,8 dB	3	116,0	12,7	1,82
2-Hop N=4, +11,8 dB	4	116,0	13,34	1,44

5. SYSTEM CAPACITY AND SPECTRAL EFFICIENCY

In addition to the End-to-End throughput studied in the previous sections, the system capacity, i.e. the aggregate traffic that can be carried in a well-defined service area and a certain amount of used spectrum is an important measure to assess a system's performance. To optimise a system, it is very important to have a clearly defined optimisation goal. The relay concept presented in this paper aims at providing a cost-efficient broadband coverage that can rapidly be deployed in a relatively large area. Table 1-1 shows the average End-to-End cell throughput for the different 1- and 2-hop deployments in the Manhattan scenario. The table also shows that the coverage area of one AP for the one-hop scenarios is relatively small, indicating that a large number of costly backbone connections is needed to cover the whole service area. From the small cell size and the high cell throughput results a relatively high area spectral efficiency. But a minimum of 4 carrier frequencies is needed in that case to provide continuous coverage. The AP deployment from Figure 1-7 (left) shows only small advantages over the horizontal/vertical placement (Figure 1-7, middle). The placement on street crossings (Figure 1-7, right) has the advantage that a larger area is covered per AP, reducing the number of needed backbone connections by a factor of 2. At the same time, a minimum of 8 carrier frequencies is needed to enable continuous coverage. This and the larger cell size lead to a substantial reduction in spectral efficiency, while the average cell throughput changes only slightly.

Table 1-2. Average Cell Capacity and spectral efficiency for a Cell with 10 MTs and Exhaustive Round Robin (ERR) Scheduling, comparing the wide-area cellular Single-Hop deployment with the Multi-Hop deployment (with and without Antenna Gain between AP and FRSs)

Scenario	Used # of Freq.	Cell Size $[m^2] / 10^3$	Cell Capacity [Mbit/s]	Spect. Efficiency $[bit\ s^{-1}\ Hz^{-1}\ m^{-2}]$
Standard 200m	3	104	6,84	1,10
Standard 200m	7	104	12,2	0,84
Standard 200m	12	104	16,42	0,66
3FRS	3	311	4,21	0,23
3FRS	7	311	7,27	0,17
3FRS	12	311	9,46	0,13
Standard 346m	3	311	6,53	0,35
Standard 346m	7	311	11,42	0,26
Standard 346m	12	311	14,82	0,20
3FRS +11,8dB	3	311	7,44	0,40
3FRS +11,8dB	7	311	11,14	0,26
3FRS +11,8dB	12	311	13,41	0,18

Another reduction of the number of APs needed (to a total factor of 4) can be achieved by using FMTs as proposed in Figure 1-6. This leads to a very cost-efficient cellular coverage of the service area. The 2-hop transmission obviously reduces the cell capacity, an effect that can be reduced through the use of higher re-use distances.

A substantial increase in throughput and cell capacity is achieved through the use of directive receive antennas at the FMTs.When using 2 carrier frequencies, the relay concept with directive antennas achieves roughly the same area spectral efficiency (2.31 $bit \times s^{-1} \times Hz^{-1} \times m^{-2}$) as the 1-hop deployment with APs on street crossings (2.37 bit×s-1×Hz-1×m-2), with the advantage of a lower number of APs and carrier frequencies needed.

Table 1-2 shows the average End-to-End cell throughput for the different 1- and 2-hop deployments in the wide-area scenario. Again, from the small cell size and the high cell throughput results a relatively high area spectral efficiency in the case of the 200 m-cells. However, the interesting observation is that the relay-based system achieves the same area spectral efficiency as a one-hop system with the same overall cell size. At the same time, as we have seen in Figure 1-12, the coverage quality at the cell border is superior in the two-hop case. Under dense frequency re-use (N=3), the two-hop system even exhibits a [14]% higher spectral efficiency (compare lines 7 and 10 of Table 1-2).

6. CONCLUSIONS

Modern wireless broadband air interfaces are based on MAC frames, the only exemptions being IEEE802.11a/b/g but 802.11e uses a MAC frame, too. MAC framed air interfaces have been established in this paper to be useful for relaying in the time domain by just using the functions available from the existing standards. Deployment concepts using fixed relay stations have been shown to be of high benefit to substantially reduce the cost of interfacing APs to the fixed network (owing to a substantial reduction of APs needed). Relays have been proven to substantially extend the radio coverage of an AP, especially in highly obstructed service areas. Gain antennas at FRSs have been established to substantially contribute to increase the throughput at cell areas far away from an AP.

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