Fixed Relays for Next Generation Wireless Systems - System Concept and Performance Evaluation

Ralf Pabst, Norbert Esseling, and Bernhard H. Walke

Abstract: **This work presents a concept and the related analysis of the traffic performance for a wireless broadband system based on fixed relay stations acting as wireless bridges. The analysis focuses on the important performance indicators end-to-end throughput and delay, taking into account the effects of an automated repeat request protocol. An extension to a MAC frame based access protocol like IEEE 802.11e, 802.15.3, 802.16a, and HIPERLAN2 is outlined and taken as basis for the calculations.**

The system is intended for both dense populated areas as an overlay to cellular radio systems and to provide wide-area broadband coverage. The two possible deployment scenarios for both dense urban and wide-area environments are introduced. Analytical and validating simulation results are shown, proving the suitability of the proposed concept for both of the mentioned scenarios.

It is established that the fixed relaying concept is well suited to substantially contribute to provide high capacity cellular broadband radio coverage in next generation (NG) cellular wireless broadband systems.

Index Terms: **Cellular radio, fixed relays, multi-hop, urban scenario, wide area, wireless broadband.**

I. 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 mobile 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 analysis, 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 IEEE 802.11e, 802.15.3, 802.16a, and HIPERLAN2. The latter system is taken to exemplify a detailed solution. This paper focuses on the analytical evaluation of the presented relaying concept. Section II presents the most important parameters and the deployment scenarios used to obtain the performance results. Section III provides the analytical background for the evaluation and presents first results. Section IV answers the question under what circumstances a relay based 2-hop transmission should be preferred to an 1-hop transmission between mobile terminal (MT) and AP. Section V performs a validation of the presented analysis against existing results of computer simulations. Conclusions are drawn in Section VI.

A. Related Work

An introduction, overview and literature survey on the concept of fixed relays to enhance coverage and capacity of wireless networks is given in [1]. That article also cites work complimentary to this one, focusing on the enhancements of wide-area cellular networks through relays, e.g., [2]. Many of the concepts presented envisage an ad-hoc extension to cellular architectures, while our approach goes towards a fully planned, yet flexible infrastructure mainly enabling increased coverage of wireless broadband networks.

Other work targeting the area of multi-hop communication has to a large extent been focused in the past on the topic of mobile ad-hoc networks (MANETs) [3]. The performance of internet protocols (TCP/IP) over MANETs is well understood (see for example [4] and [5]).

However, there are paramount differences between MANETs and wireless networks based on the deployment of fixed relays. (I) In the latter case, the position of the nodes participating in a communication is known and thus the routing overhead that presents one of the major issues in MANETs is not present here. (II) Fixed relays do not exhibit power limitations because they are expected not to be battery-operated, but they still do contribute to a reduction of overall transmission power levels.

Previous work on analytical estimation of the capacity of networks based on fixed relays has mostly approached the issue from the view-point of information theory, thereby deriving theoretical performance bounds as shown in [6] and [7]. This paper takes into account a specific protocol approach that fits into the framework of existing standards with a periodic MAC frame structure. It thereby focuses on a relaying-enabled medium access control (MAC) and a selective-repeat type automatic repeat request (ARQ) protocol.

B. Characteristics of the Relaying Concept

Relaying is widely acknowledged as a means to improve capacity and coverage in wireless broadband networks, see [1].

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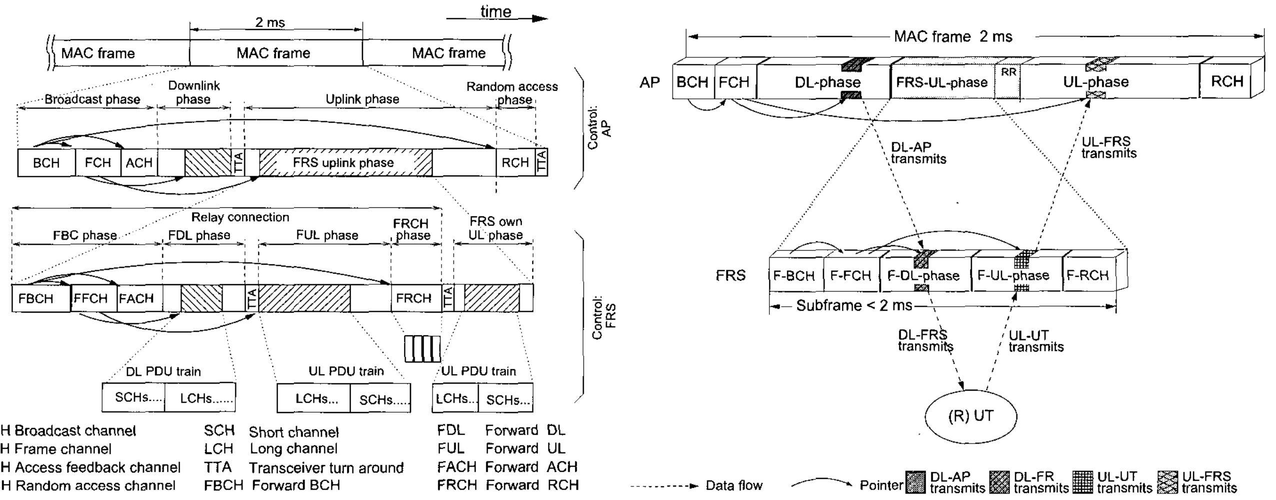


(a) (b)

Fig. 1. Example: Relaying based on H2 protocol extensions; (a) standard-conformant enhancements of the H2 MAC frame, (b) data flow using a sub-frame in 2-hop mode.

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, while at the same time **reducing transmission power levels**. In the case of the access points and relay stations, this will contribute to the public acceptance of such systems, while in the case of the mobile terminals it has the potential to increase battery lifetime.

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. In this case, a FRS serves another FRS according to the needs besides serving the mobile terminals (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.

C. 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 through the MAC protocol software only.

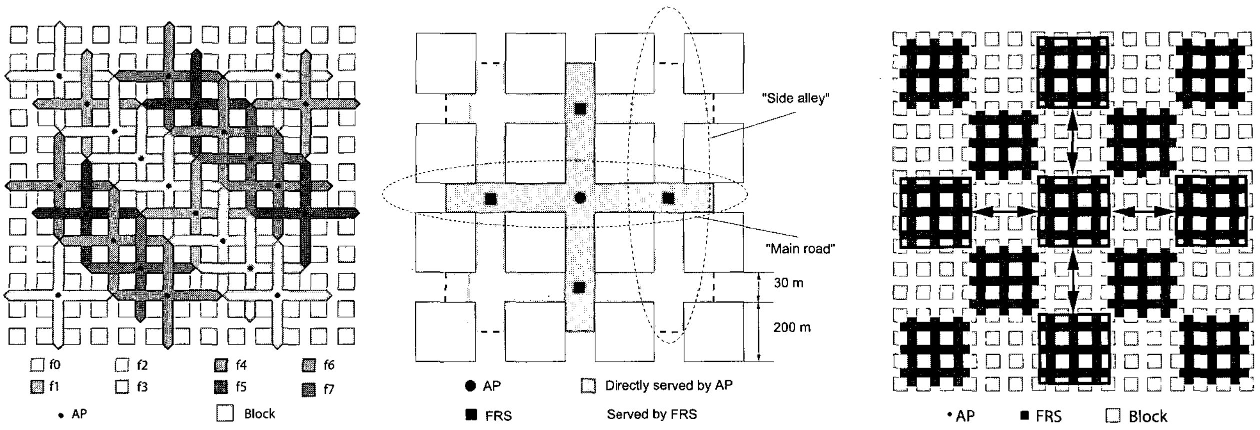
Relaying in the frequency-domain: This concept uses different carrier frequencies on links a FRS is connecting. The two hops can be operated independently of each other at the cost of increased complexity of the hardware and the frequency management.

Hybrid time-/frequency-domain relaying: In the hybrid concept as investigated in [8], 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 scenario shown in Fig. 2(b) are presented.

D. 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



(a) (b) (c)

Fig. 2. One- and two-hop deployment concepts for dense urban environments; (a) exemplary AP deployments and co-channel placement without relays, (b) relay-based cell with four relays in the Manhattan scenario, (c) city-wide coverage with relay-based cells for cluster size $N = 2$.

(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, Fig. 1(a). In the forwarding mode (FM), both signaling and user data are being forwarded by the FRS. A 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 also referred to as remote mobile terminals (RMTs) if they are served by a FRS.

The capacity of the MAC frame (see Fig. 1(a), upper part) is assigned dynamically in a two-stage process [9]. Transmit capacity for terminals directly associated to the AP (FRSs and MTs) is allocated by the AP. A 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 (see Fig. 1(a), 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 Fig. 1(b)) 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 they 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.

Fig. 1(a) 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. For more details, see [9]. A very similar operation is possible by using the hybrid coordinator access in IEEE 802.11e.

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

II. SCENARIO AND ASSUMPTIONS ABOUT ENVIRONMENT

A. Scenario

A.1 Dense Urban Area

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 defined by [10] has been taken for the following investigations, see Fig. 2(b). The most important parameters of the scenario are the block size of 200 m and the street width of 30 m. An exemplary deployment scenario without relays is shown in Fig. 2(a), each of the APs covers the range of two building blocks and one street crossing, resulting in 430 m range.

The variant shown here is has the APs placed on street crossings, 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 sufficiently far by cells using a different frequency. Other variants used in the comparison are the AP placement according to [10] and the (very similar) placement of APs between buildings at equal x- and y-coordinates (referred to as "same height").

The scenario shown requires 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

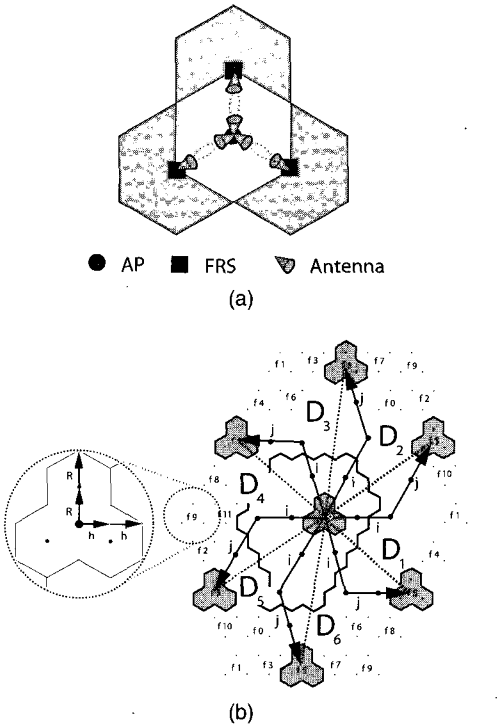


Fig. 3. Wide area relay-based deployment; (a) relay-based cell with three relays, (b) reuse shift parameter for a $N = 12$ relay-cell cluster.

based on relaying. The basic building block, which consists of an AP and 4 FRSs is shown in Fig. 2(b). It has the potential to cover a much larger area than one single-hop AP.

In this evaluation, the location of the FRS is assumed to be at a fixed distance of 230 m from the AP, with the MT moving along the horizontal and vertical streets at varying distance, as indicated in the pictograms included in the result graph.

Fig. 2(c) 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 $D = 1380\ \mathrm{m}/2070\ \mathrm{m}/2760\ \mathrm{m}$.

A.2 Wide Area

It is a known fact that wireless broadband systems exhibit low coverage range at high bitrates [11]. In a conventional 1-hop 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. Fig. 3(a) 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 FRS 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 (cf., Fig. 3(b)). Different cluster sizes (here regarded $N = 3, 7, 12$) can be realized with the basic element just like in the traditional hexagonal cellular approach. Like in the urban area evaluation presented above, the location of the FRS is assumed to be at a fixed distance of 200 m from the AP, with the MT moving along the horizontal and vertical axis at varying distance, as indicated in the pictograms included in the result graph.

B. 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, and 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 subcarriers. The modem is assumed conformant to the IEEE 802.11a standard. As indicated in Section I, 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 adressed by the proposed relaying concept.

III. ANALYTICAL BACKGROUND

This section presents the analysis corresponding to the results displayed in Figs. 7(b) and 8. Most of these figures also include performance evaluation results obtained by stochastic-event driven simulation, which have been published in [12]. The mathematical symbols used in this section are explained in the following.

PL_{Path}: Resulting pathloss (attenuation)
PL_{FS}: Free-space component
k_{wi}: Number of transmitted walls of category i
PL_{wi}: Attenuation of wall type i
b_{wi}: Correction factor
L_{Ges}: Number of OFDM symbols per MAC frame
L_{Org_1Hop}: Number of symbols for organization channels
L_{Neg_Ack}: Symbols for negative acknowledgement
$n_{Neg\_Ack\_Phy\_x}$: Number of acknowledgements needed
$L_{Data\_Phy\_x}$: Symbols for a data packet in PHY mode x
p_{BCH}: Error probability on boadcast channel
p_{FCH}: Error probability on frame description channel
$p_{Data\_Phy\_x}$: Error probability for a data packet in PHY mode x
p_{F-BCH}: Error probability on FRS boadcast channel
p_{F-FCH}: Error probability on FRS frame description channel
p_{1Hop}: Error probability on first hop
p_{2Hop}: Error probability on second hop

A. 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 extensive link-level investigations performed in [13] provide a PDU error-probability related to the average $C/(I + N)$ (taking into account co-channel interference) during reception of the PHY-PDU. This relation is shown in Fig. 4.

B. Propagation and Interference

As stated in the introduction, it is envisaged that future broadband radio interfaces will be characterised by a very limited range due to the very high operating frequencies (>5 GHz) expected. Investigations of propagation phenomena in the targeted frequency range ([14], [15]) indicate that diffraction around edges will substantially decrease with increasing carrier frequencies so that the direct transmission path and its obstructions gain more importance.

Owing to the fact that cyclic-prefix OFDM systems exhibit an inherent robustness against multipath delay (see [16]), we assume that the obvious error induced by neglecting the reflection of waves is sufficiently small to justify this simplification when the performance of higher layer protocols on top of such OFDM systems is in the focus of interest.

Another rationale for the choice of a rather simple propagation model is that more detailed models consequently require a detailed modeling of the receiver, which is beyond the scope of this work. Receiver properties have been implicitly assumed by taking up the link-level results from [13].

Note that the accuracy of the presented analysis does not suffer from the choice of the propagation model, since the analysis is based on the PDU-error probabilities only.

Following the above considerations, the fairly simple COST259 multi-wall model has been chosen as propagation model. This model [17] is originally an indoor propagation model for the 5 GHz frequency range, which takes into account the transmission through walls obstructing the LOS between transmitter and receiver. Unlike in the COST231 model [18], the attenuation non-linearly increases with the number of transmitted walls. The pathloss is

$$PL_{Path} = PL_{FS} + \sum_{i=1}^{l} k_{wi}^{\left[\frac{k_{wi}+1,5}{k_{wi}+1} - b_{wi}\right]} PL_{wi}. \tag{1}$$

The wall attenuations have been chosen according to the suggestions made in [19], which have been found to sufficiently model the urban scenario presented here.

The signal to noise plus interference ratio $C/(I+N)$ can then be calculated like this

$$\frac{C}{I+N} = \frac{P_{Rx}}{P_N + \sum_{i=1}^{n} P_{I_i}}, \tag{2}$$

with $P_N = -95\,\text{dBm}$ being the reiceiver noise floor for the 20 MHz channel, P_{Rx} the received signal power (including the path loss) and P_{I_i} the received interference power from each interferer i. With the assumption about the scenario geometry and a fixed transmission Power of all stations of 23 dBm, it is possible to calculate $C/(I+N)$ values for all positions in a given scenario.

C. Throughput

The values L_{Ges}, L_{Org_1Hop}, and L_{Org_2Hop} define the capacity that can be made available in one MAC frame. In combination with the knowledge about the re-transmission behaviour of the automatic repeat request (ARQ) protocol (influenced by the PDU error probabilities as gained using the calculated $C/(I+N)$-values in Fig. 4), this leads to the formulas for the throughput as presented in the following.

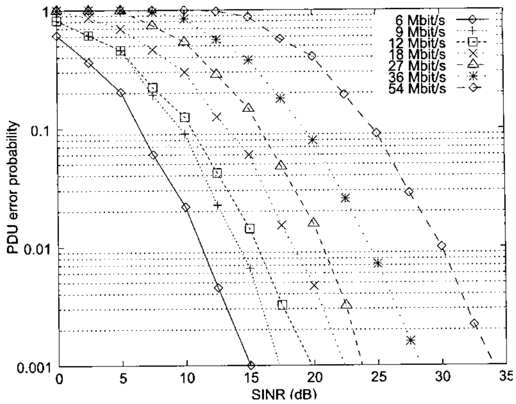


Fig. 4. PDU-error probability for varying $C/(I+N)$ and PHY-mode, based on [13].

C.1 1-Hop System

The resulting throughput for 1-hop end-to-end connections with ARQ is described by the following equation.

$$D_{ARQ\_1Hop\_Phy\_x} = \frac{(1-\nu_{1Hop})(L_{Ges} - L_{Org\_1Hop})}{(L_{Neg\_Ack} \cdot n_{Neg\_Ack\_Phy\_x} + L_{Data\_Phy\_x} \cdot n_{ARQ\_Phy\_x})} \cdot \frac{48 \cdot 8bit}{2ms}, \tag{3}$$

where ν_{1Hop} is the capacity loss due to erroneous detection of the broadcast channel (BCH) and/or the frame channel (FCH), given through,

$$\nu_{1Hop} = 1 \cdot p_{BCH} + 1 \cdot (1 - p_{BCH}) p_{FCH}. \tag{4}$$

The number of necessary negative acknowledgements necessary for the successful transmission of a packet ranges from 3 to 24. In the case of multiple re-transmissions, the average number of necessary negative acknowledgements is then given through

$$n_{Neg\_Ack\_Phy\_x} = \sum_{k=0}^{\infty} \frac{k \cdot (1 - p_{Data\_Phy\_x}) p_{Data\_Phy\_x}^{k}}{\max(3\,;\, 24 p_{Data\_Phy\_x}^{k})}, \tag{5}$$

while $n_{ARQ\_Phy\_x}$ denotes the number of necessary packet transmissions and can be approximated by

$$n_{ARQ\_Phy\_x} \approx \frac{1}{(1 - p_{Data\_Phy\_x})}. \tag{6}$$

C.2 2-Hop System

The total throughput for 2-hop end-to-end connections with ARQ is defined in analogy to (3) and is described by the following equation.

$$D_{ARQ\_2Hop\_Phy\_x} = \frac{(1-\nu_{2Hop})(L_{Ges} - L_{Org\_2Hop})}{2(L_{Neg\_Ack} \cdot n_{Neg\_Ack\_Phy\_x} + L_{Data\_Phy\_x} \cdot n_{ARQ\_Phy\_x})} \times \frac{48 \cdot 8\text{ bit}}{2\text{ ms}}. \tag{7}$$

The factor $\frac{1}{2}$ is introduced because the end-to-end throughput and not the overall system throughput is described in the expression. The simplifying assumption was made that both the first and the second hop are ecountering similar conditions.

In the 2-hop case, the capacity loss ν_{2Hop} due to erroneous detection of the broadcast channel (BCH) and/or the frame channel (FCH) becomes more complex, because we now have to take into account the BCH and FCH phases of the FRS, denoted as F-BCH and F-FCH. It is given through the following expression

$$\begin{aligned}\nu_{2Hop} &= 1\cdot p_{BCH}+\frac{1}{2}(1-p_{BCH})p_{FCH}\\ &+ \frac{1}{2}(1-p_{BCH})p_{FCH}\\ &+ \frac{1}{2}(1-p_{BCH})(1-p_{FCH})p_{F-BCH}\\ &+ \frac{1}{2}(1-p_{BCH})(1-p_{FCH})\\ &\cdot(1-p_{F-BCH})p_{F-FCH}, \end{aligned}\tag{8}$$

where all p_{x-y} depend on the $C/(I+N)$ and the used PHY mode on the respective hop.

The influence of the different hops on the end-to-end throughput is investigated in the following. Fig. 5(a) shows the throughput as a function of the $C/(I+N)$-values on the respective hop. Fig. 5(b) shows selected cross-sections through the surface from Fig. 5(a). The $C/(I+N)$-value on the first hop is used as a parameter. The relation between the channel quality on the first hop and the end-to-end throughput is obvious. With a $C/(I+N)$ of 32 dB on the first hop, the transmission capacity is only limited by the second hop.

D. End-to-End Delay

This subsection presents the analysis of the influence of the ARQ protocol on the end-to-end delay. The results of the 2-hop case are compared with the reference results for the 1-hop case.

The analysis presented is based on a number of assumptions.

- We regard a selective-repeat ARQ.
- The delay is dominated by re-transmissions.
- The delay is determined as multiples of 1 MAC frame.

First, we have to determine the probability for a protocol data unit (PDU) to be successfully transmitted via a 1-hop link after exactly j retransmissions. As a function of the packet error probability p, the result is

$$P_{=}(j)=(1-p)p^{j}. \tag{9}$$

As a consequence, the probability of up to j retransmissions is given by the sum

$$P_{\leq}(j)=\sum_{l=0}^{j}(1-p)p^{j}. \tag{10}$$

For the 1-hop end-to-end relation, we immediately find.

$$P_{=1Hop-E2E}(j)=P_{=1Hop}(j). \tag{11}$$

For the 2-hop link, the probability for the number of retransmissions is composed from all possible combinations of the sum

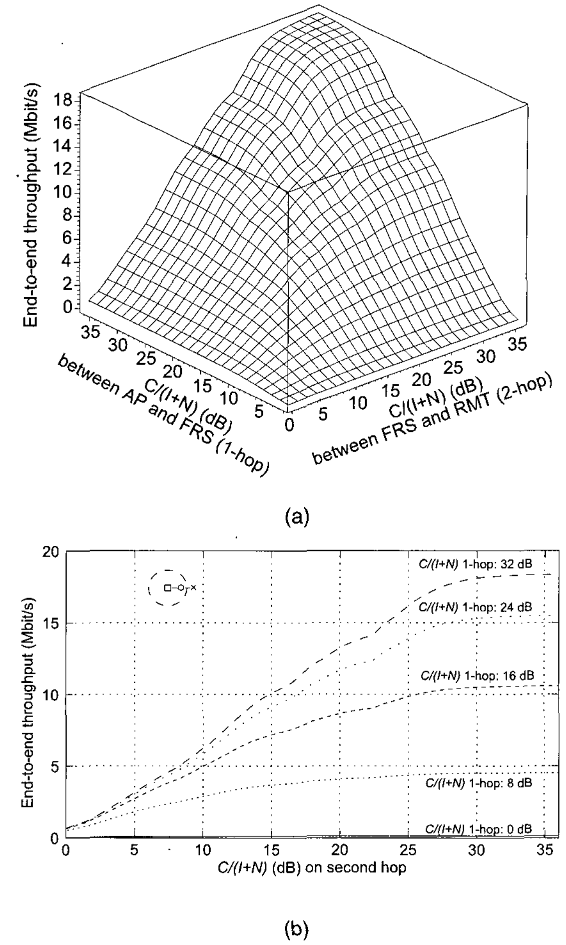


Fig. 5. Maximum ARQ-E2E-throughput vs. $C/(I+N)$-values on the respective hops; (a) overview, (b) for specific $C/(I+N)$-values on first hop.

of the retransmissions on the respective hops. The end-to-end probability thus becomes

$$P_{=2Hop-E2E}(j)=\sum_{l=0}^{j}P_{=1Hop}(j)P_{=2Hop}(j-l). \tag{12}$$

D.1 ARQ Delay for Small Data Rates

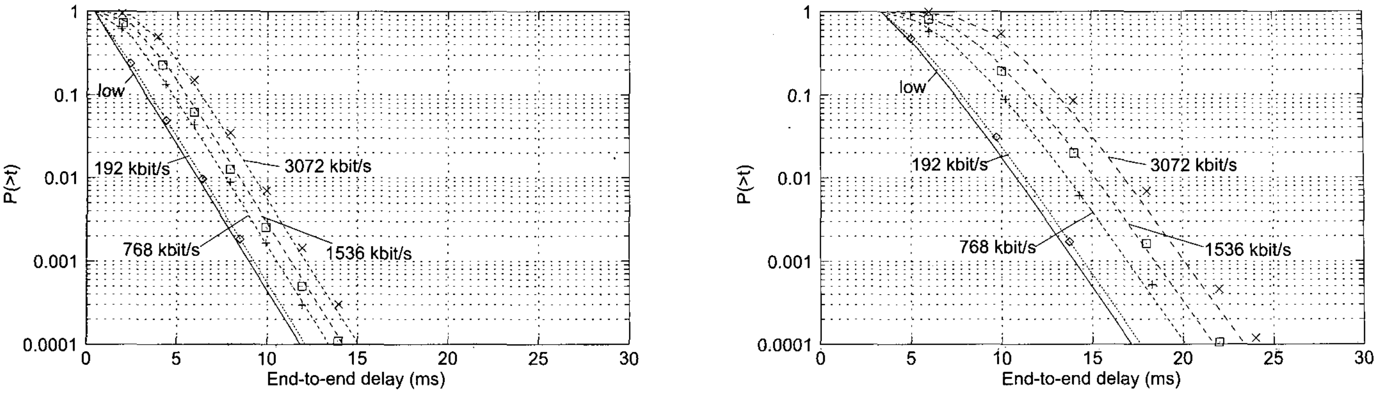
In the case of connections with small data rates (small data rates are assumed to consume an average of less than one PDU per MAC frame) the packets can be assumed to be independent.

1-Hop System: In the one-hop case, the probability p_{1Hop} for erroneous transmission of a PDU which has to be used in (10) is

$$\begin{aligned}&p_{1Hop}=\\ &1-\left[(1-p_{BCH})(1-p_{FCH})(1-p_{1Hop_{Data\_Phy\_x}})\right].\end{aligned}\tag{13}$$

From this, the distribution function of the 1-hop end-to-end delay can be derived when the delay caused by j retransmissions is known.

2-Hop System: In the one-hop case, the probability p_{2Hop} for erroneous transmission of a PDU which has to be used in



(a)

(b)

Fig. 6. End-to-end-delay for connections with different data rates, depending on a fixed packet error probability $p = 0,2$ (Analysis: Lines; simulation: Markers); (a) 1-hop-downlink, (b) 2-hop-downlink.

(10) is

$$p_{2Hop} = 1 - [(1 - p_{BCH})(1 - p_{FCH})(1 - p_{F-BCH}) \cdot (1 - p_{F-FCH})(1 - p_{2Hop_{Data\_Phy\_x}})]. \quad (14)$$

From this, the distribution function of the 2-hop end-to-end delay can be derived when the delay caused by j 2-hop-retransmissions is known.

D.2 ARQ Delay for High Data Rates

In the previous model, the independence of the single PDUs was assumed. This assumption is only fair for small data rates, where the average number of PDUs per MAC frame is considerably lower than one. For connections with higher data rates, multiple PDUs are transmitted per MAC frame. Thus the forwarding of a PDU depends on all previous PDUs unsuccessfully transmitted in the same frame. It has to wait for the sequence to be "repaired." In the following, we assume that we have an arriving traffic of n PDUs per MAC frame. $\mathrm{PDU}_{i,x}$ belongs to MAC frame i and has position x with $x \in [1 \cdots n]$. The variables u with $u \in [1 \cdots n]$ and m with $m \in [1 \cdots \infty]$ serve to describe the relation between $\mathrm{PDU}_{i,x}$ and $\mathrm{PDU}_{i-m,u}$ in frame $i - m$ at position u. Here, we have to distinguish 3 cases that contribute to the distribution function $P_n(k)$ for the number of MAC frames k that a PDU has to wait for its delivery. $P_n(k)$ depends on the number of PDU arrivals per MAC frame n.

Case 1: $\mathrm{PDU}_{i,x}$ needs k frames. All previous PDUs in the same and all previous frames have been received correctly. The probability that $\mathrm{PDU}_{i,x}$ is delayed by k frames then becomes

$$P_{Case1(x,k)} = P_{=}(k) P_{\leq}(k)^{(x-1)} \prod_{m=0}^{\infty} P_{\leq}(k+m)^n. \quad (15)$$

Case 2: $\mathrm{PDU}_{i,x}$ needs $k - 1$ frames, one of the previous $\mathrm{PDU}_{i,y}$ ($y \in [1 \cdots x-1]$) from the same frame i needs k transmissions. Here, all $\mathrm{PDU}_{i-m,u}$ ($m \in [1 \cdots \infty]$) from previous frames are received at the latest together with $\mathrm{PDU}_{i,y}$. The probability that $\mathrm{PDU}_{i,x}$ is delayed by k frames then becomes

$$P_{Case2(x,k)} = P_{\leq}(k-1) \prod_{m=0}^{\infty} P_{\leq}(k+m)^n P_{\leq}(k) \cdot \sum_{y=1}^{x-1} P_{\leq}(k)^{(y-1)} P_{\leq}(k-1)^{x-1-y}. \quad (16)$$

Case 3: At least one $\mathrm{PDU}_{i-m,u}$ ($m \in [1 \cdots \infty]$) from a previous frame needs k transmissions. Now the PDUs of the currently regarded frame ($\mathrm{PDU}_{i,x}$ and $\mathrm{PDU}_{i,y}$ with $y \in [1 \cdots x - 1]$) require a maximum of $k - 1$ transmissions. The probability that $\mathrm{PDU}_{i,x}$ is delayed by k frames then becomes

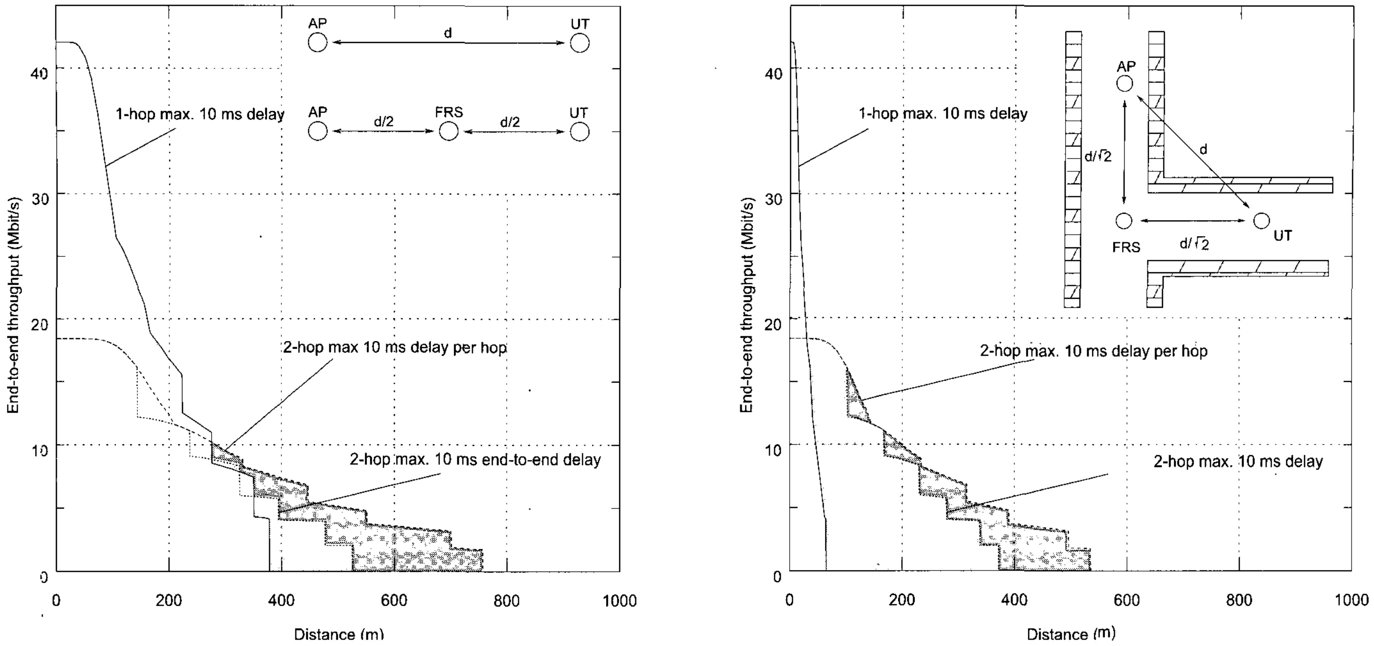
$$P_{Case3(x,k)} = P_{\leq}(k-1)^x \cdot \sum_{m=1}^{\infty} \left[\begin{array}{l} \prod_{s=1}^{m-1} P_{\leq}(k-1+s)^n \cdot \\ \prod_{t=1}^{\infty} P_{\leq}(k+m+t)^n P_{=}(k+m) \cdot \\ \sum_{u=1}^{n} P_{\leq}(k+m)^{u-1} P_{\leq}(k-1+m)^{n-u} \end{array} \right]. \quad (17)$$

The resulting combined error probability for a delay of $i + k$ frames, averaged over the n PDUs arriving during a frame then becomes

$$P_n(k) = \frac{1}{n} \sum_{x=1}^{n} P_{Case1(x,k)}(x,k) + P_{Case2(x,k)}(x,k) + P_{Case3(x,k)}(x,k). \quad (18)$$

In addition to the probabilities given in (15), (16), and (17), we need knowledge about the delay caused by j retransmissions on the 1-hop and 2-hop connections to be able to draw the delay distribution functions for 1-hop and 2-hop traffic. As a result of limiting the delay precision to multiples of one MAC frame, this is trivial and will not be shown here.

Fig. 6 shows the end-to-end delay for a fixed PDU error probability pf $p = 0,2$. A varying traffic offer of 192 kbit/s, 768 kbit/s, 1536 kbit/s, and 3072 kbit/s, corresponding to $n = 1, 4, 8$, and 16 PDUs per frame with constant inter-arrival time for the 54 Mbit/s-PHY-modes was investigated. The curve labelled "low" denotes the theoretical lower bound for very low



(a) (b)

Fig. 7. Analytical comparison of the maximum achievable end-to-end throughput over distance for a 1- and 2-hop connection with ARQ under 10 ms maximum end-to-end-delay restriction; (a) LOS condition, (b) around an obstacle.

data rates (e.g., $n < 1/10$), where capacity for acknowledgements is assumed present and used in every frame.

IV. 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. Fig. 7(a) compares the end-to-end throughput achieved with 1-hop and 2-hop transmission for the two scenarios depicted in the upper right corner of the respective figures under line of sight (LOS) radio propagation. Since the systems in question have delay-sensitive high-bandwidth applications as one of their main targets, an additional condition imposed here is that an upper bound of 10/ms end-to-end delay restriction has to be met in both the one- and the two-hop case.

For this simple comparison, it is assumed without loss of generality that the FRS is placed at half the distance between the AP and the (R)MT. A more detailed evaluation is presented later in this paper, which also takes into account varying ratios of AP-FRS and FRS-RMT distances by assuming a fixed position of the FRS with respect to the AP and a varying position of the RMT.

In the simple comparison presented here, it turns out that from a distance of 240 m onwards, the 2-hop communication is able to deliver a slightly higher throughput than 1-hop, as marked by the light shaded area. It can also be noted that the range of the 1-hop transmission is limited to about 380 m, while the 2-hop transmission reaches 500 m, still keeping the 10 ms delay constraint. Under the somewhat weaker constraint of 10 ms delay per hop, the coverage of the 2-hop solution even reaches 750 m, visualized by the darker shaded area.

Relay based 2-hop communication provides another considerable benefit already mentioned in Section I-B. 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 Fig. 7(b), together with the throughput gain (light-shaded: 10 ms end-to-end delay constraint, dark-shaded: 10 ms per-hop delay constraint) 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 III-B) 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 about 50 m only. The two examples shown here establish that relaying is of advantage for both, increasing the throughput close to the cell border of an AP (under LOS conditions) and for providing radio coverage (and throughput) to areas otherwise shadowed from the AP.

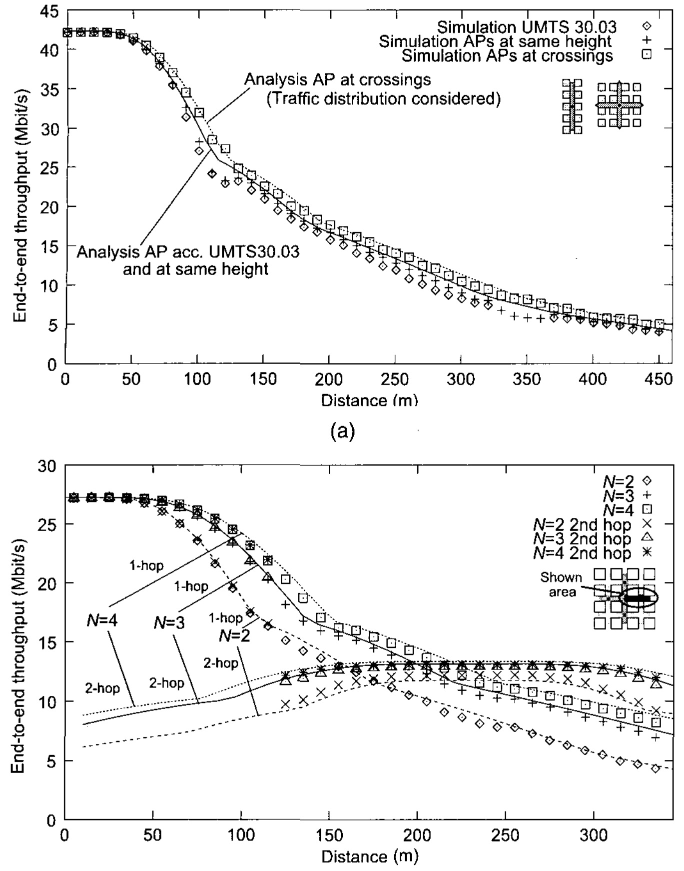
The trend towards increasing transmission rates resulting from further developed radio modems tends to provide an over capacity in the cell area served by an AP, especially in the first months/years after deploying a system. Relays substantially increase the size of the service area thereby increasing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

V. VALIDATION OF RESULTS

This section compares and validates the results of the analysis presented before with simulation results the authors have presented in [12].

A. Reference Scenario without Relays

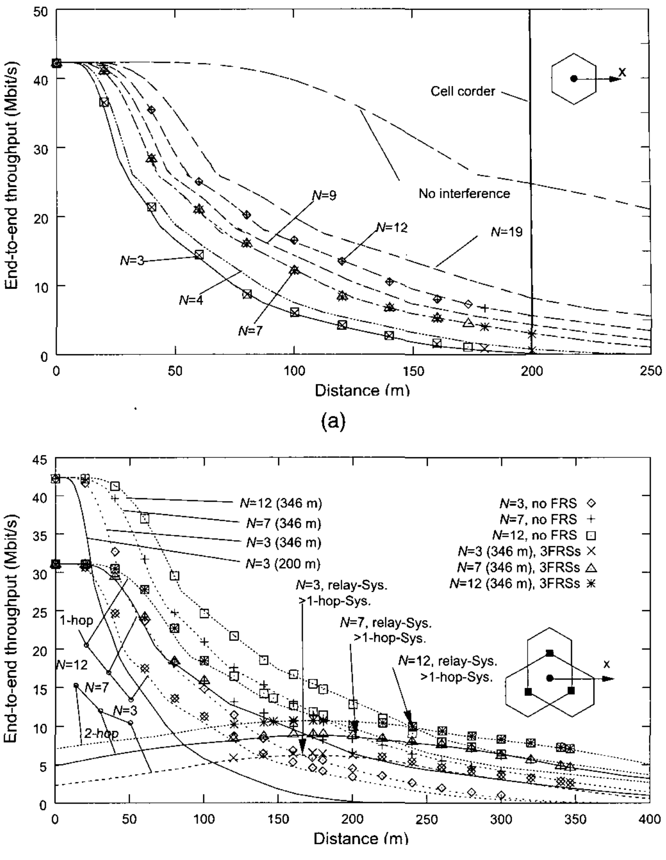
In Fig. 8(a), the DL end-to-end throughput is plotted over the distance of the MT from the AP when servicing the scenario



(a)

(b)

Fig. 8. Urban scenario: End-to-end-throughput along the "main road" (see pictogram) without (top) and with relays (bottom) (Lines: Analysis, markers: Simulation); (a) E2E-throughput downlink, 1-hop, (b) E2E-throughput downlink, 2-hop "main road" (with gain antenna).



(a)

(b)

Fig. 9. Wide area scenario: End-to-end-throughput along the "x-Axis" (see pictogram) without (top) and with relays (bottom) (Lines: Analysis, markers: Simulation); (a) E2E-throughput downlink, 1-hop, (b) E2E-throughput downlink, 2-hop "x-axis" (with gain antenna).

by APs only according to Fig. 2(a). At distances of 115 m and 345 m (where the street crossings are located), some additional interference is visible. The figure also shows that the simulation results match the analytical prediction very well, except from said crossing areas.

Fig. 9(a) 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 $N = 19$. Here again, the analytical predictions match the simulation results quite well.

Fig. 6(a) shows the end-to-end-delay for connections with different data rates, depending on a fixed packet error probability $p = 0,2$ (Analysis: lines; simulation: Markers). Here again, the simulation results validate the analytical prediction quite well.

B. Simulation Results with Fixed Relay Stations

Simulations with fixed relays as introduced in Section II-A have been performed for the cluster sizes $N = 2/3/4$ in the dense urban case and $N = 3, 7, 12$ in the wide-area case, cf., Figs. 2(c) and 3.

Fig. 8(b) shows two sets of curves in one graph: The TP versus the distance of a MT from the AP (marked with 1 hop) and the TP avilable for MTs being served by a FRS (marked with 2 hop), which is equipped with a 11.8 dB receive antenna gain. The FRS is located at a distance of 230 m from the AP on the "main road" (cf., the small scenario included in the figure and Fig. 2(b)). This explains the peak of the "2 hop" TP 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 TP values. A max. TP of approx. 9–12 Mbit/s (depending on N) can be made available even at the cell border of the second hop, representing an increase in peak throughput of about 60–90%. The same is true for the "side alley" (not shown), 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.

The left-hand side of Fig. 9 shows the maximum achievable downlink end-to-end throughput versus the distance (in x-direction) of a MT from the AP.

The right-hand side of Fig. 9 shows the maximum achievable downlink end-to-end throughput versus the distance (in x-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). The FRS are located at a distance of 200 m from the AP (shown in the pictogram). The maximum of the 2nd-hop throughput curve can be found where the terminal's distance from the FRS is minimal.

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 left part of Fig. 9 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 figure represents the situation encountered by terminals moving along the x-axis (also refer to the small pictograms included). For direct comparison, the single hop case (no FRS, $R = 346$ m) is also included in the figure.

Depending on the cluster-size, the maximum end-to-end throughput along the x-axis improves for ranges greater than 170 m ($N = 3$), 200 m ($N = 7$), and 240 m ($N = 12$) when relay stations are used instead of a single hop deployment.

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 smaller the cluster-size, the smaller gets the minimal range where the use of FRSs is beneficial. With lower cluster sizes, the number of necessary frequency channels is reduced. This allows to use more frequency channels per cell and thus to increase network capacity. When using FRS, 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 (if equal site density is regarded), the advantages of the relay-based concept already become visible at distances > 30 m from the AP, as visible from Fig. 9(b).

VI. CONCLUSIONS

Modern wireless broadband air interfaces are based on MAC frames, the only exemptions being IEEE 802.11a/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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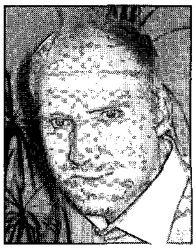

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