Multi-hop based Radio Network Deployment for efficient Broadband Radio Coverage

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***Abstract*— It is widely accepted that multi-hop communication will become an integral element in *beyond 3G* (B3G) broadband networks, because the area that can usually be covered by a single *Access Point* (AP) is inherently small. This paper elaborates on the potential of a *fixed* and *planned* multi-hop architecture for the extension of range and for the coverage of otherwise shadowed areas in B3G systems. We particularly focus on a scenario where the range of an AP is extended by one or more *Relay Stations* (RS), each having a receive antenna gain. Based on a set of assumptions on the technologies and paradigms used in such systems we quantify the achievable throughput in the area covered by a RS and illustrate its inter-dependencies with some system parameters such as AP transmit power, pathloss coefficient, relaying strategy and RS receive antenna gain. We show that substantial increases in peak throughput can be achieved through multi-hop relaying. This helps to make the very high capacity of a broadband access point available in a larger area than its original coverage, meeting the expected spatial distribution of the traffic demand more precisely. We propose and compare different mechanisms of relaying in the time domain for a planned infrastructure. Based on these mechanisms we show that the introduction of relay based deployment concepts can substantially increase the capacity of a single AP.**

I. Introduction

The coverage area of a single *Base Station* (BS) of future broadband radio systems is likely to be very small compared to recent mobile communication systems of the 2^{nd} and 3^{rd} generation due to the expected low transmission powers that allow high frequency reuse at low interference and due to high attenuation of the expected spectrum bands which are likely to be at 5 GHz or above. Consequently, a sufficient wide area coverage can only be applied at the cost of an increased number of “pico cellular BSs” resulting in high deployment costs.

A cost efficient and innovative solution is to trade capacity against range by partly utilising the capacity of an *Access Point* (AP), i.e. a single “pico cellular BS”, by a number of *Relay Stations* (RS), which act as wireless BS to provide radio coverage in areas that are out of range or shadowed (no direct *Line Of Sight* (LOS) to the AP). The advantage over pico-cellular BSs is that the RSs do not need a wired network connection, which is the determining cost factor. This solution appears also very attractive since it is deemed unlikely that the high traffic capacity of a broadband AP will be used up by the user terminals roaming in its original coverage area [1]. The relaying concept applies to wide area as well as to short-range systems. An extensive discussion of this system concept, called *Wireless Media System* (WMS), can be found in [2]–[4].

We use the following terminology:

Access Point (AP): An AP is a BS that is directly connected to the fixed network, either via fibre or via another air interface, e.g., Microwave LOS Radio, etc.

Relay Stations (RS): A RS is *wirelessly* connected to an AP, having relay functions either in layer 3, 2, or 1. We distinguish Fixed RS (FRS) and Mobile RS (MRS). A FRS/MRS appears to the terminals in its service area like a BS, while it appears like a terminal to its serving AP.

Media Point (MP): Both base station elements, the AP and the FRS, will be further referred to as Media Point.

In the following we restrict our investigations to FRSs.

The FRSs may be located at different places, e.g., on rooftops, walls of buildings or even lampposts. Such positioning has the side-effect that power supply is often available and advantageous LOS propagation can be arranged through proper planning.

The technology of relaying is not new, but in the past relaying was in most cases applied in conjunction with ad-hoc networking, which leads to dynamic network topologies and requires sophisticated routing strategies [5], [6]. In this paper, the potential of relaying technologies for the use in mobile broadband systems with a *fixed infrastructure* is discussed. Some results already exist in this field as described by N. Esseling et. al. in [7] for HiperLAN/2. Their results are based on existing systems originally designed to work in single hop mode.

The scenario our analysis is based on is described in Section II. In Section III the parameters and their impact on performance and cost of a multi-hop based system are discussed, before we show some analytical results to illustrate the impact of these parameters in Section IV. Section V concludes our paper.

II. Scenario and Modelling

The investigated multi-hop system uses the same OFDM modem as used by HiperLAN/2, IEEE 802.11a or the W-CHAMB system [6]. Link level simulation results [8] for the packet error rate (PER) as a function of the Signal to Noise Ratio (SNR) from a 5GHz HiperLAN/2 system with 20 MHz channel bandwidth have been used as a basis for the analysis. The throughput of the proposed multi-hop system has been calculated as physical layer throughput without considering protocol header overhead. Retransmissions from a selective reject ARQ protocol are taken into account. Further we assume an optimal link adaptation allowing to operate always on the PHY-mode which delivers the highest throughput as shown in Fig. 1 by the fat dashed curve.

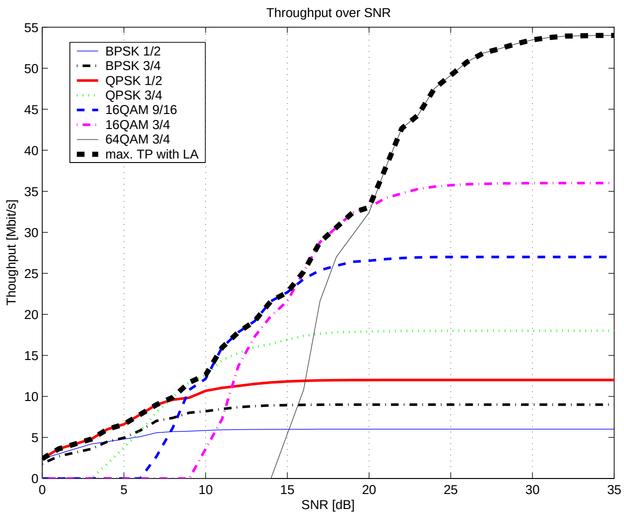

Fig. 1. OFDM Modem with optimal Link Adaptation [8]

In the analysis no interference from co-channel APs or FRSs is taken into account. The background noise was assumed -96 dBm. For calculating the relation between received SNR and distance from the transmitter we use the following simple path loss model [9]:

$$P_R = P_T \cdot g_T \cdot g_R \left(\frac{\lambda}{4\pi}\right)^2 \cdot \frac{1}{d^\gamma}. \quad (1)$$

P_R denotes the received signal power in Watt, P_T the transmitting power in Watt, g_T and g_R are the receiver and transmitter antenna gains, resp., λ is the wavelength of the transmitted signal, d is the distance between the transmitter and the receiver and γ is the pathloss coefficient. We assumed $\gamma = 3.5$ for non LOS (NLOS) conditions and $\gamma = 3$ for the LOS path in urban areas.

The FRS are assumed to use omni-directional antennas to serve their associated mobile terminals. AP and FRS are transmitting on the same frequency, unless otherwise stated. Consequently, it is assumed that only one can transmit at a time. This principle is called *time-domain relaying*.

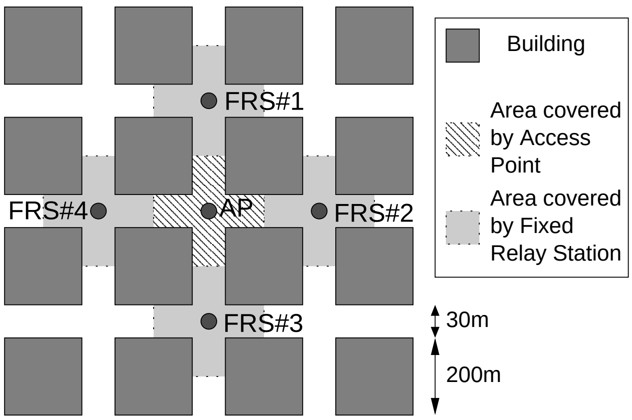

Fig. 2. 2-Hop cell in Manhattan scenario

Fig. 2 shows a *2-Hop-Cell* in the assumed Manhattan scenario [10]. The 2-Hop Cell is comprised by 5 *Sub-Cells*, one *Central Cell* covered by the AP and four *Relay Cells* covered by the FRSs. Each MT will be accessed with max. two hops. The streets in the assumed scenario are 30 m wide and the building blocks are sized 200 m x 200 m. Within this paper the MPs are located one in the middle of each intersection, i.e. 230 m apart.

III. Relaying Techniques and Parameters

In order to evaluate the feasibility of relaying concepts it has to be shown that the sufficient traffic performance can be maintained even at the end of each hop-chain. At the same time the relaying technology has to be as simple as possible to maintain the cost advantage.

In the following we investigate the impact of the different parameters on a wireless broadband radio system. In addition to the parameters in Eq. (1), the *hop depth*, which is the maximum number of transmissions a packet has to undergo, will be examined.

The transmission power P_R has an impact on the range of each MP, either AP or FRS and on the available PHY mode and with it the throughput.

The use of antennas with gain seems only recommendable for the MPs due to cost and terminal size/complexity considerations. At the FRS the antenna gain plays an important role to increase the throughput. Due to the requirement that the FRS should look like a regular terminal to the AP, we assume that there is only a FRS receive antenna gain.

The pathloss coefficient itself cannot be influenced, but it depends on the scenario topology and the conditions on the transmission path. Due to employment of FRSs a "virtual" LOS condition between receiver and transmitter can be established almost everywhere, as the FRSs can be used to "look around the corner" and cover otherwise shadowed areas. Thus, we can assume a much lower mean path loss coefficient, compared to the mean path loss coefficient that is required to model usual transmission paths through or around obstacles.

The number of hops is a system-inherent parameter. It is obvious that a high number of hops increases the delay and affects the throughput. Furthermore the number of hops is directly related to the scenario geometry in order to benefit from the effect that a smartly positioned relay can cover otherwise shadowed areas.

Relaying can be performed in different domains, e.g., time-domain, frequency domain or code-domain. In the following relaying in the frequency and time domain will be investigated.

IV. Performance Analysis

A. Multi-Hop Chain

To show the effect of trading capacity against range we firstly investigate a scenario with an AP feeding one FRS that in turn feeds another FRS and so on. This scenario is called *multi-hop chain*.

Figure 3 shows the peak throughput that can be achieved in a multi-hop chain with 3 FRSs resulting in max. 4 hops as a function of the distance from the AP. Assumptions are that AP and FRSs all have LOS connections between them (Distance d=230 m, $\gamma = 3$). They operate in the 5 GHz band. The transmission power was set to the maximum of 20 dBm allowed in this frequency range and the FRSs were assumed to have a receive antenna gain of 16 dBi. For the connection between MP (either AP or FRS) and MT also LOS conditions with $\gamma = 3$ have been assumed.

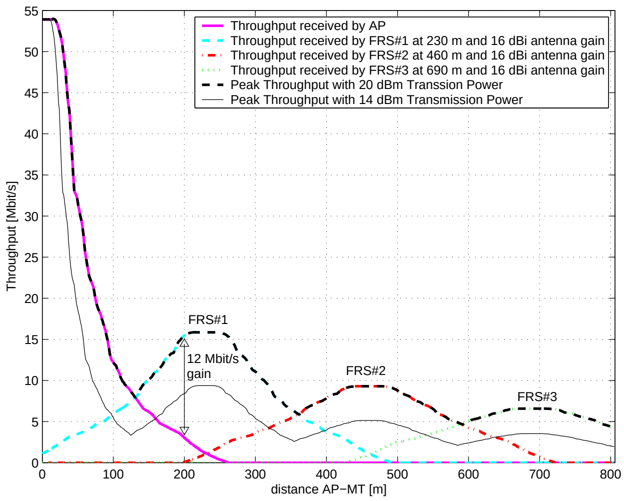

Fig. 3. Max. throughput for a four-hop connection

The envelope (dotted curve) has to be compared with the throughput of the AP to get an impression of the tremendous gain that can be achieved in terms of peak throughput (order of 400 % at 200 m). This effect can be expected to further increase under heavier shadowing.

The throughput that can be achieved by the MT from the AP roaming within a "multi-hop chain" with N FRSs in a row can be calculated by

$$TP_{AP-MT} = (\frac{x}{TP_{MP-MP}} + \frac{1}{TP_{MP-MT}})^{-1} \qquad (2)$$

with x ϵ {0,1,2, ...,N}.

TP_{MP-MP} is throughput achievable between two MPs. This throughput depends on the distance between two MPs and on the antenna gain. It is assumed that all MPs receive equal throughput from their feeding MP, excluding the loss on previous hops. TP_{MP-MT} is the throughput achieved on the MP to MT link. x indicates the number FRS included in the multi-hop connection between the AP and the MT with $x = 0$ if the MT is served directly by the AP.

This gain in the peak throughput can also be exploited to reduce the overall transmission power in order to reduce the human radio exposure and/or to be aware of new regulatory constraints. To trade the peak throughput against tranmission power some requirements have to be defined, i.e. that after the reduction of the transmission power still a sufficient traffic performance must be available. We assumed that a minimum peak throughput of 2 Mbit/s is required at every site in the coverage area. This results in a required transmission power of $P_T = 14\,\mathrm{dBm}$ as shown in Fig. 3.

B. 2-Hop Cell with multiple FRSs

As shown in the last section, the throughput decreases with an increasing number of hops. Therefore in this section a *2-Hop Cell* with four FRSs is investigated as shown in Fig. 2.

The most simple case of forwarding is in the time domain with *equal time share* of the capacity [11]. The time frame of a system with four FRSs fed by one AP is shown in Fig. 4. For a better differentiation we will further refer to this case as *Case 1*. It can be seen that the time slot allocated to feed the MTs in the "Forwarding Cell" is split into two parts, one to transmit the data packet from the AP to the FRS (1^{st} hop) and one to transmit the data packet from the FRS to the MT (2^{nd} hop). The time required for the transmission on the first hop, $T_{Hop1} = T_{AP-FRS} = D_L/TP_{AP-FRS}(G, d_{AP-FRS})$, is mainly dependent on the antenna gain ($G = G_R + G_E$) and on the distance between the AP and the FRS, d_{AP-FRS}. TP_{AP-FRS} is the throughput available between the AP and a FRS. D_L is the length of the transmitted data packet.

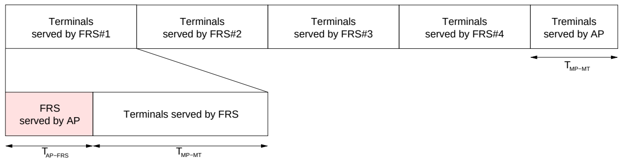

Fig. 4. Case 1: Time frame for pure TDMA relaying

Obviously, the solution shown above is very inefficient. Therefore, the overall capacity of the 2-Hop cell can be enhanced by exploiting the spatial independency of some of the "Forwarding Cells". Spatial independency in this case means that the cell areas of two or more FRSs are fully shadowed from each other as shown in Fig. 2 for, e.g., FRS#1 and FRS#2 or FRS#2 and FRS#3, etc. In the case of spatial independent "forwarding cells" neither, e.g., FRS#1 nor any MT in the cell of FRS#1 will cause any interference to the cell of FRS#2 and vice versa. This allows to exploit space division for these two "forwarding cells" resulting in a time frame as shown in Fig. 5. Now two of the the four FRSs can transmit in parallel in a time. This approach, named *Case 2*, is obviously only possible in a planned infrastructure and has to be adapted individually for each scenario a fact that is true also for the cases shown below.

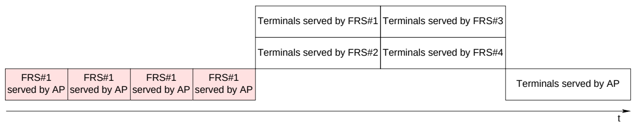

Fig. 5. Case 2: Time frame with 2x2 spatial independent "forwarding cells"

To allow all four FRSs to serve their MTs in parallel more carrier frequencies are required. Thereby, due to the fact that always two "forwarding cells" are spatially decoupled in this scenario, one more frequency channel is enough to allow all four FRSs to serve their MTs in parallel. Spending one more frequency channel to allow the AP to serve its MTs leads to the channel structure as shown in Fig. 6. But this relaying mechanism, named *Case 3* in this paper, costs three times more spectrum than the pure time domain relaying as described before. On the other hand the multi-hop cell receives a higher flexibility to react on interfering systems, which are very likely to occur in license exempt band, by the simple rotation of the allocated frequencies between the FRS groups and the AP.

As shown in the picture the total time for one multi-hop frame $T_{2-hop-cell} = 4 * T_{AP-FRS} + 1 * T_{MP-MT}$. Thus the throughput for this relaying mode can be calculated as

$$TP = (\frac{4}{TP_{AP-FRS}} + \frac{1}{TP_{MP-MT}})^{-1}. \qquad (3)$$

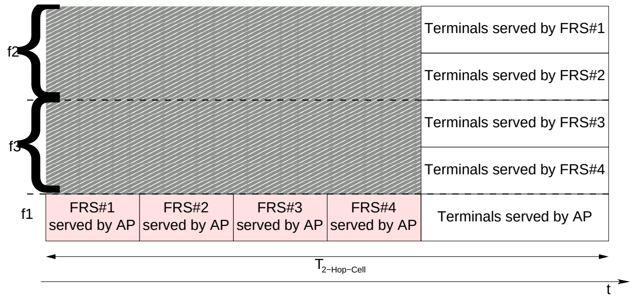

Fig. 6. Case 3: Channel Structure with 2x2 spatial independent "forwarding cells" and 3 frequency channels

This equation looks quite similar to Equation 2, but unlike in the multi-hop chain case the capacity of the AP in this scenario does not only feed one MT, but is extended by the capacity of the four FRSs. This capacity is gained at the cost of a comparably small amount of capacity required to feed the FRSs.

Fig. 6 illustrates that most of the time is consumed by feeding the FRSs. Obviously, there are two possibilities to enhance the system, on one hand the FRSs can be fed in parallel which would reduce the "feeding time"for the first hop by 4 and on the other hand the time to feed one FRS can be reduced.

In *Case 4* we propose to use the unused spectrum (frequency channels $f2$ and $f3$ in Fig. 6) to feed the FRSs. This means that we use the 3 fold spectrum as compared to Case 1-3 on the first hop. Simplified we assume that we therewith increase the throughput on the 1^{st} hop by factor 3.

A parallel transmission on the first hop can be realised by using Smart Antennas on this hop between AP and FRSs, further referred to as *Case 5*. This solution can be further enhanced by increasing the throughput due to the exploitation of the additional spectrum as proposed for Case 4 already. The resulting frame of *Case 6* is shown in Fig. 7.

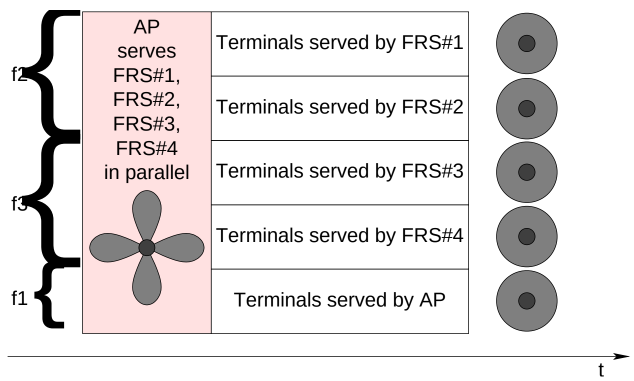

Fig. 7. Case 6: Frame with smart antenna technology at AP and 3 frequency channels

In Fig. 8 the throughput of the different forwarding techniques is shown over the distance. As reference mark the achievable throughput of an AP without RSs is shown as (solid black curve). Obviously, there is some loss due to the introduction of relays if a single cell is viewed. For the analysis the antenna gain received at the FRS was assumed to be 16 dBi, the pathloss coefficient was set to $\gamma = 3$ for the connection between the AP and the FRSs (LOS) and $\gamma = 3.5$ for the connection between the MP and the MT (NLOS). The frequency was set to 5 GHz and the transmission power was set to 20 dBm.

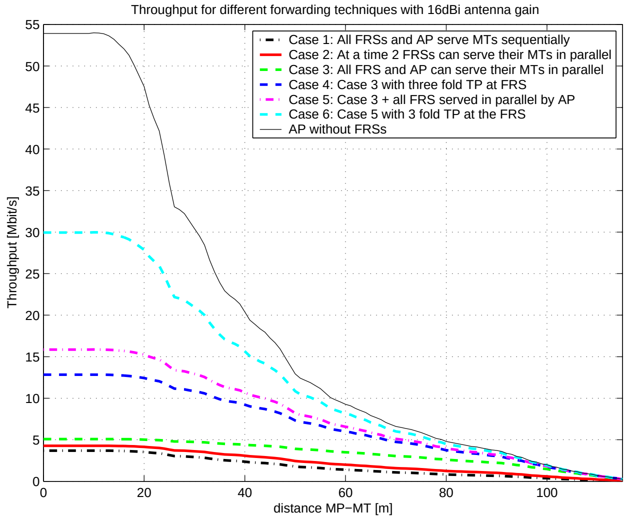

Fig. 8. Throughput for different forwarding techniques ($G_S + G_R$=20 dBi)

C. Capacity

To show the gain of the introduced relaying concepts the capacity of an AP feeding the 4 FRSs was calculated by means of the following formula as given in Eq. 4 [11]:

$$C = \frac{5N_{sc}}{\sum_{j=1}^{N_{sc}} \frac{1}{TP_{AP-MT}(d_j)} + 4 \cdot \sum_{k=1}^{N_{sc}} \frac{1}{TP_{FRS-MT}(d_k)}} \quad (4)$$

N_{sc} denotes the number of users in each of the 5 sub-cells, either forwarding cell or central cell. d_k and d_j are the distances of uniformly distributed users.

In Fig. 9 the capacities of the different cases of forwarding as introduced in Section IV-B are shown over the antenna gain available between the AP and the FRSs. The capacity shown is always the capacity of one AP, feeding the related FRS, i.e. the capacity of the whole 2-hop cell, as the whole traffic is going through the AP. As reference the capacity of an AP without FRS is given as a dashed horizontal line. Like for the throughput analysis in Fig. 8 the pathloss coefficient was set to $\gamma = 3$ for the connection between AP and FRS and $\gamma = 3.5$ for the NLOS connections of MT and MP. The transmission power was set to 20 dBm. It was further assumed that the users are equally distributed in the cell with a density of 0.1 user per square meter. To calculate the capacity the covered area was divided into circular areas containing the same number of users.

Naturally, the capacity of the AP increases in all relaying cases with an increasing antenna gain. As for the throughput the most impressive capacity gain occurs for the cases with three frequency channels and at best with smart antennas to feed the FRSs in parallel. To achieve a fair comparison between the capacity of an AP with and without relaying the capacity of the single AP using 3 frequency channels is also given as reference (upper dashed, horizontal line).

It is very interesting to see that the capacity of *Case 2* is exceeding the capacity of a single AP already with an antenna gain of around 7 dBi. This is possible due the effect that an increased number of users can be served with high data rates from the AP point of view. Even the capacity *Case 1* comes close to the capacity of the single AP, which means that the time spent to feed the FRSs is quite low compared to the time required to feed the MTs. For a system with 16 dBi antenna gain the capacity gain ranges from -0.47 Mbit/s for a system as proposed in Case 1 up to 7.2 Mbit/s for a system as proposed in Case 3 compared to the capacity of a single AP without any relays, which was calculated 3.75 Mbit/s. The approaches described as Case 4 to 6 have been compared against an AP with 3 frequency channels (3 fold capacity) as they utilise either 3 frequency channels or at least enhanced antenna technologies at the AP. This results in an capacity gain of 3.91 Mbit/s for *Case 4* up to 6.45 Mbit/s for *Case 6*.

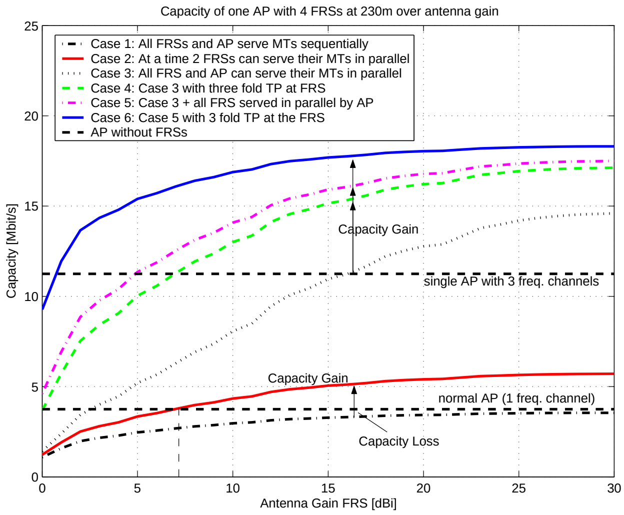

Fig. 9. Capacities of AP feeding 4 FRS 2-Hop cell vs. antenna gain for different relaying techniques

The advantage of the relaying system would increase even more if a scenario is assumed where large area are out of sight of the AP due to obstacles, i.e. that the users in this areas have only little or no access to the AP. In this case the capacity as shown in Fig. 9 would stay the same for the multi-hop cases and the reference value of the stand-alone AP would decrease due to the limited coverage or decreased throughput.

V. Conclusion

The introduction of a multi-hop component in future cellular broadband systems is a very attractive solution to the problem of having too much capacity available in a too small area, especially regarding urban scenarios, which are characterised by very short LOS paths.

On the other side the multi-hop approach adds several additional dimensions to the parameter space that have to be explored in order to find optimised parameter sets. In this context there is the need for a general understanding of the impact the newly introduced system parameters have on the achievable traffic performance.

In this paper we have shown that infrastructure based relaying can be used to trade capacity against range with an tremendous increase of the peak throughput.

We have shown that the required transmission power can be significantly reduced compared to a single-hop system that covers the same area. The FRS's receive antenna gain determines how much of the AP's capacity can be transferred to the outer margins of the cell.

Further, we introduced some ideas to realise such relays by taking advantage of the spatial independency of sub-cells by otherwise disturbing obstacles and illuminated the capacity gain of the different relaying methods.

Although the analytical results are based on a very specific scenario and on ideal system assumptions, they point out the system inherent potential of relay based systems with fixed and planned infrastructure.

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