Capacity of a Relaying Infrastructure for Broadband Radio Coverage of Urban Areas

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***Abstract*— Owing to the difficult propagation conditions in the frequency range of future cellular broadband radio systems, very small cell sizes and high attenuation through obstacles (sufficient C/I ratio only in direct Line of Sight (LoS)) are expected to constitute a major challenge for the development of such systems. Thus, complete coverage of urban areas using a conventional (one-hop) cellular infrastructure is expected to be very costly due to the high number of base stations and fixed network connections needed. For this reason, the introduction of relaying is widely accepted to be an essential element in the development of future cellular broadband radio networks. This paper presents a methodology to quantify the influence of relaying on the capacity of a single base station. We define the capacity as the aggregate downlink throughput that is achieved by all users in the cell. Inspired by the recently proposed Wireless Media System (WMS) architecture [1], we compare the capacity of a conventional one-hop cellular architecture with the capacity of a configuration consisting of one base station and four regenerative Fixed Relay Stations (FRS) that together cover the same area like five base stations in a conventional cellular architecture. The presented methodology allows to explore the parameter space, which is spanned by system parameters like antenna gain, scenario geometry, noise and transmit power.**

I. Introduction

Future broadband radio interface technologies and the related high multiplexing bit rate will dramatically increase the traffic capacity of a single Base Station (BS), so that it is deemed very unlikely that this traffic capacity will be entirely used up by the user terminals roaming in the cell. This effect will be amplified by the fact that future broadband radio interfaces will be characterised by a very limited range due to the very high operating frequencies which can be expected from such systems. Furthermore, future broadband radio interfaces will be characterised by high attenuation due to obstacles, leading to big areas that are shadowed from the BS.

An innovative solution to this class of problems is to trade capacity against range by introducing a number of Relay Stations (RS), which serve to enlarge the coverage area of a BS. This is achieved by introducing a receive antenna gain (RX gain) at the RS, enabling the RS to connect to the BS in a distance outside the coverage area of the BS, and/or to receive from the BS at a data rate that is substantially higher than without RX gain. This concept will also solve the attenuation problem in a cost efficient way by extending the range of the BS to areas behind obstacles.

In this context we address the question of how the multiple transmission of user data affects the capacity that is available in the coverage area of one BS. We present a methodology for calculating the capacity of a configuration called *2-Hop-Cell*, which is based on the relation between throughput and distance. This relation is derived from the well-known link-level simulation results presented in [2] by assuming an ideal SREJ-ARQ protocol. We then extend this relation to areas covered by a RS by calculating the resulting throughput that can be achieved when user data is transparently transmitted via one of the RSs.

Based on the assumption of

- uniformly distributed users in the cell's coverage area,
- a given user density
- and equal traffic offer per user

we determine the cell capacity, which is defined as the aggregate downlink throughput of all users served by the cell.

For the purpose of clear terminology we introduce the following:

- Access Point (AP): a BS that is directly connected to the fixed network.
- Fixed Relay Station (FRS): a BS connected wirelessly to an AP. An FRS appears to the terminals in its service area like a BS.
- Mobile Terminal (MT): the user's end device
- Infrastructure Element: generic term for both FRS and AP

A. Ad-hoc Relaying vs. Infrastructure-based Relaying

The idea of multi-hop transmission originates from the research area of ad-hoc networking, nevertheless it is very important to clearly distinguish between ad-hoc networking and relaying. Ad-hoc networking is predominantly characterized by an a priori *unknown and dynamic topology*, while relaying simply means that user data is transmitted more than one time before it reaches its destination node. Relaying is part of most ad-hoc networking approaches, but in our scope it is considered to be part of a *fixed and planned topology*. The important difference in this case is that the routing matrix is known and remains constant over time, so that certain benefits of multihop relaying can be exploited to a significantly larger extent.

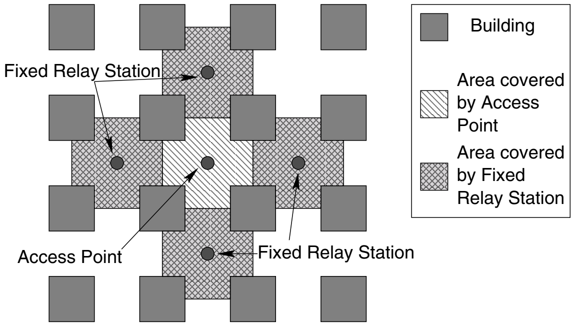


Fig. 1. Schematic view of a 2-hop-cell in a Manhattan scenario

B. Related Work

An excellent introduction into the whole area of multihop transmission in wireless networks, including the introduction of a clear terminology, is provided by Yanikomeroglu [3].

The most widely known approach to the capacity of wireless networks has been introduced by Gupta and Kumar [4]. One reason for us to choose a different approach is that Gupta and Kumar assume a wireless network without centralized control, where all nodes randomly access a common radio channel. Within our scope, presence of a central radio resource management for the coverage area of one AP (including the areas covered by the AP's FRSs) is foreseen. It is immediately clear that the question of how much traffic can be carried by a given configuration has to be adressed completely different under the presence of a centralized scheduling instance. The second reason is that Gupta and Kumar aim at general network topologies, which can be arbitrary and randomly chosen. Our research is targeted at a more specific scenario, therefore our approach was selected with respect to the possibility to incorporate scenario-specific aspects.

II. Scenario and System Architecture

In the scope of this paper we focus on application of multihop relaying concepts in urban scenarios, which are widely agreed to be well represented by a Manhattan-type scenario [5]. Fig. 1 shows a schematic view of the radio coverage in a city center that is based on one AP, which is connected to the fixed network, and four FRSs that connect wirelessly to the AP. We call this configuration a *2-Hop-Cell*. A MT roaming around the area covered by the 2-Hop-Cell is served by the closest FRS or AP.

The same area that is covered by the 2-hop-cell can be covered using an array of 5 BS as part of a conventional cellular (one-hop) architecture, by replacing each FRS with an AP. We will compare the 2-hop-cell with such a configuration in a way that these 5 BSs share the same amount of frequency spectrum that is available for the operation of the 2-hop-cell. This means that one of these BSs either has only a 20% share of the total available spectrum, or that the 5 BS have to be multiplexed in the time domain, both of these alternatives are equivalent to our analysis.

As our approach requires a given relation between Packet Error Ratio (PER) and Signal to Noise Ratio (SNR), we assume a fictitious multi-hop system that uses the same physical layer as it is used in the HiperLAN/2 or IEEE 802.11a system. The relation $PER = f(SNR)$ is taken from the well known link level simulation results presented by Khun-Jush et. al. [2] for a 5GHz Hiperlan/2 system with 20MHz channel bandwidth. As this physical layer consists of several parameter sets, each resulting in a different physical layer bit rate (these parameter sets are called *PHY-modes*), we assume ideal link adaptaion, which means that at any time the PHY mode that delivers the best possible throughput is chosen automatically.

A. Time-domain Forwarding and TDMA

We assume forwarding in the time domain, i.e., a packet that is addressed to a FRS-served MT is first transmitted from the AP to the FRS and afterwards immediately forwarded to the MT using the same frequency channel; see Fig. 2. Furthermore, we assume a pure TDMA system without any kind of *optimized* scheduling, which means that our capacity figures do not contain the potential benefit of sending packets from AP to one FRS parallel to the transmission of packets from another FRS to one of the MTs served by this FRS. This leads to a linear packet transmission scheme which is depicted in Fig. 2.

III. Relay Throughput Calculation

IIn the scope of this paper we regard two path radio propagation, which is modeled by [6]:

$$P_R = P_S \cdot g_S \cdot g_E \cdot \left(\frac{\lambda}{4\pi}\right)^2 \cdot \frac{1}{d^\gamma}. \quad (1)$$

We calculate the distance where a given SNR is valid, which leads to a relation between PER and distance from the BS. In the next step we assume an ideal SREJ-ARQ protocol, and calculate the resulting relation between throughput and distance from the BS; see the solid curve in Fig. 3. Any protocol overhead has been neglected for our calculations. Furthermore, no interference has been included. Radio coverage of BS and FRSs is assumed to be only straight ahead without coverage around corners (direct LoS).

We assume that the FRSs are equipped with directed receive antennas. This is a reasonable assumption, since the AP's location can be assumed to be known by the FRS. This results in an improved throughput-distance relation between AP and FRS, as denoted by the dashed curve in Fig. 3. The troughput between the FRS and a MT that is served by the FRS obviusly obeys the same relation like for transmission between AP and MTs served by the AP (solid and dashed curve, resp.).

To calculate the throughput between AP and a MT that is served by a FRS we proceed as follows: let TP_{hop1} denote the transmission rate on the first hop (AP to FRS), which is determined by evaluating the dashed curve in Fig. 3 at the given FRS location. Further let $TP_{hop2}(d)$ denote the transmission rate on the second hop (FRS to MT), depending on the distance of the regarded MT, d, which is given by

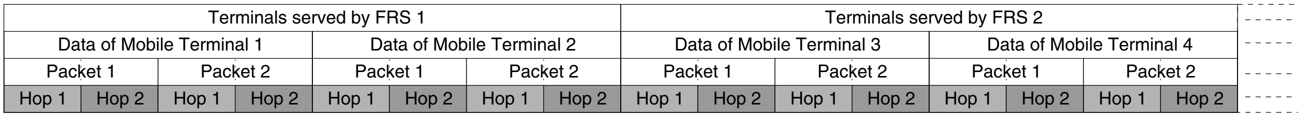


Fig. 2. Relaying in the time domain

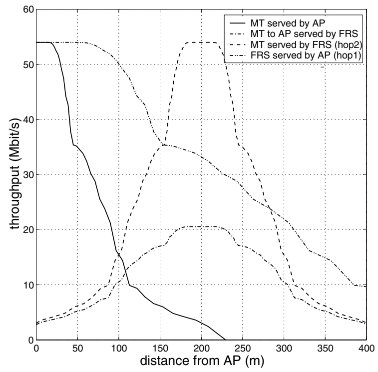


Fig. 3. Throughput for separate hops and end-to-end throughput for MTs served by FRS

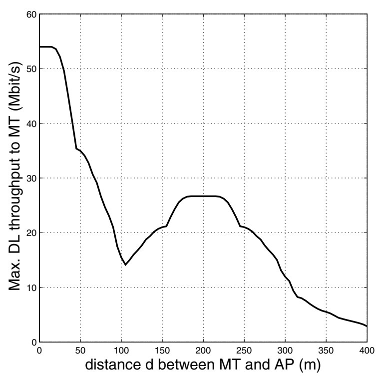


Fig. 4. Throughput relations used for capacity evaluation

the dashed-double-dotted curve of Fig. 3. The transmission durations of a packet size P are $t_{hop1} = {}^{P}/_{TP_{hop1}}$ and $t_{hop2} = {}^{P}/_{TP_{hop2}(d)}$. The total duration of a two-hop transmission, $t = t_{hop1} + t_{hop2}$ then leads to the relation between offered throughput by a FRS and distance between MT and AP:

$$TP_{FRS} = \left(\frac{1}{TP_{hop1}} + \frac{1}{TP_{hop2}(d)} \right)^{-1} \qquad (2)$$

This relation is depicted by the dashed-single-dotted curve in Fig. 3. We now define the border between the AP's coverage area and the FRS's coverage area to be exactly the point where the solid curve meets the dashed-dotted curve, which is equivalent to the assumption that an intra-2-hop-cell handover from AP to FRS is performed when the achievable FRS throughput exceeds the AP throughput. If we now take the envelope of these two curves, this relation defines the maximum achievable throughput at any location in the 2-hop-cell coverage area. This figure, called TP_{max} in the following, is shown in Fig. 4.

IV. Cell Capacity

In the case only one user is present in the cell, the cell's capacity is given by the maximum throughput the user is able to achieve. This throughput depends on the user's location, as described in the previous section. Unfortunately a single user can no longer maintain this throughput if the capacity has to be shared between several users, because only one user can transmit at a time, and the others have to remain silent (TDMA system). Thus, time represents the critical resource that has to be shared.

Assume two MTs at distances d_1 and d_2 with equal traffic offer A. The achievable throughput of these MT's at d_1 and d_2 is denoted by $TP_{max}(d_1)$ and $TP_{max}(d_2)$. Transmision of P bytes of data then takes $t_1 = {}^{P}/_{TP_{max}(d_1)}$ and $t_2 = {}^{P}/_{TP_{max}(d_2)}$, respectively. As these two transmissions have to take place one after another, the total service time for *both* MTs is $t = t_1 + t_2$. If we now conceive this service time as the duration of a fictious scheduling period, $P = P_{max}$ denotes the maximum amount of data that each MT can transmit in one scheduling period. Note that this traffic offer can also be normalized to different durations, so that it is not necessary to assume a certain duration of the scheduling period itself. The maximum traffic offer per user then computes to

$$A_{max} = \left(\frac{1}{TP_{max}(d_1)} + \frac{1}{TP_{max}(d_2)} \right)^{-1} = \frac{P_{max}}{t} \qquad (3)$$

If we now extend the calculation to N MTs located at distances $d_i, i = 1..N$, the maximum traffic offer *per user* is

$$A_{max} = \left(\sum_{i=1}^{N} \frac{1}{TP_{max}(d_i)} \right)^{-1} \qquad (4)$$

and the total transmit capacity of the cell is

$$C = N \cdot A_{max} = \frac{N}{\left(\sum\limits_{i=1}^{N} \frac{1}{TP_{max}(d_i)} \right)}. \qquad (5)$$

Please note that this relation also holds for the case that not all of the N users are served by the same infrastructure element, the only prerequisite is that each of the distances d_i has its corresponding throughput value $TP(d_i)$, and that the both the multihop transmission of a single packet, and the transmission intervals of multiple users are in strict sequence, i.e., no overlapping transmissions are allowed.

In the case of the 2-hop-cell (see Fig. 1) we can divide the number of uniformly distributed users N into 5 equal parts, $N = 5N_{sa}$, where N_{sa} is the number of users located in one of

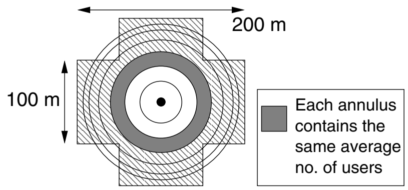


Fig. 5. For radii calculation the cell area is divided into concentric areas that contain one user each

the 5 equal coverage sub-areas of AP and FRSs, respectively. The total capacity of the 2-hop-cell then can be written as

$$C = \frac{5N_{sa}}{\sum_{j=1}^{N_{sa}} \frac{1}{TP_{AP}(d_j)} + 4 \cdot \sum_{k=1}^{N_{sa}} \frac{1}{TP_{FRS}(d_k)}}. \quad (6)$$

We now assume that the whole cell capacity is given to the users served by one of the FRSs or the AP (in this case the whole cell capacity is concentrated at one of the infrastructure elements). The capacity that is available at this FRS or AP computes to:

$$C_{FRS} = \frac{N_{sa}}{\sum_{k=1}^{N_{sa}} \frac{1}{TP_{FRS}(d_k)}} \qquad C_{AP} = \frac{N_{sa}}{\sum_{j=1}^{N_{sa}} \frac{1}{TP_{AP}(d_j)}} \quad (7)$$

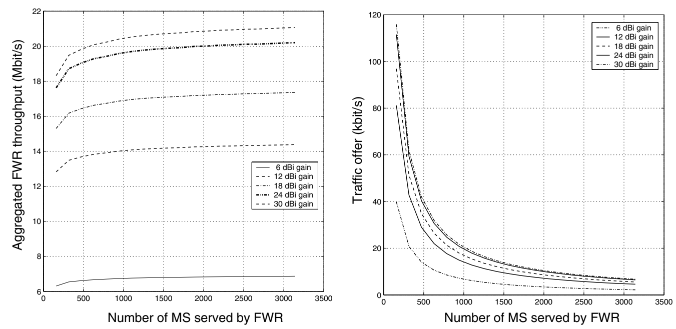
This leads to the interesting observation that

$$\frac{1}{C} = \frac{\frac{1}{C_{AP}} + 4\frac{1}{C_{FRS}}}{5}. \quad (8)$$

Thus, we can separately calculate the capacity of FRS and AP, assuming that the cell capacity is exclusively available for the users of one infrastructure element and then compute the total capacity in a second step.

A. Computing the Distances for Uniformly Distributed Users

Obviously the capacity calculated according to (5) depends on the spatial distribution of users in the cell's coverage area. We now assume that the users are *uniformly distributed* in the coverage area, with an average of N_u users per square meter. The area that contains an average of one user is denoted by $A_{user} = {}^{1}\!/_{N_u}$. We divide the cell area into concentric annuli with growing radius, so that the area in an annulus is equal to the area that contains an average of one user, $A_{i+1} = A_i + {}^{1}\!/_{N_u}$; see Fig. 5. The annuli are only complete until the radius reaches the bulding corners. This effect is included in the calculation of the subsequent radii. We further assume that the user that belongs each of these areas is located on the outer border. This way we separate the whole coverage area of a FRS or the AP into sub-areas that each contain one user. Please note that, since the throughput-distance relation is axially symmetric, only the distance between the serving infrastructure element (FRS or AP) determines which throughput is actually received, so that a unique throughput value can be assigned to each user.



(a) Capacity vs. user density

(b) Traffic offer per user vs. user density

Fig. 6. The capacity converges to a maximum when the user density grows to infinity, at the same time the traffic offer per user declines

V. 2-Hop-Cell Capacity Evaluation

The combination of the capacity evaluation procedure of Sec. IV and the radii determined according to Sec. IV-A leads to capacity figures that quantify the impact of multihop relaying on the capacity that is made available by an AP, and the amount of capacity that has to be spent for the benefit of an extended coverage area.

For the following results the scenario parameters have been chosen as follows:

- distance between building blocks: 100 m, accordingly the distance between AP and FRS is 200 m
- AP and FRS transmit power: 20 dBm
- Pathloss coefficient: $\gamma = 3$
- FRS receive antenna gain: 10-30 dBi

An interesting property of our approach to cell capacity is visible in Fig. 6. When the user density is scaled to very large values, the resulting capacity shows a convergent behavior; see Fig. 6(a), which can be explained by the fact that for high user density the area per user is very small and thus, the throughput-distance relation of Fig. 4 is "sampled" very often. The growing number of users is kept in balance by a declining traffic offer per user, as can be seen in Fig. 6(b). Obviously selecting a high user density and a low traffic offer per user increases the accuracy of the capacity evaluation procedure.

For all following results a user density of 0.01 ${}^{\text{users}}\!/_{m^2}$ was assumed. In Fig. 7 the resulting capacity of AP and FRS is evaluated for the case that the whole capacity of the 2-hop-cell is concentrated at a single infrastructure element, and the effect of varying the FRS antenna gain is visualized. The capacity of the AP (this case is equivalent to the AP operated as a conventional one-hop BS) amounts to 28.13 ${}^{\text{Mbit}}\!/_{\text{s}}$. The capacity that can be made available for the relay case, i.e., when the whole capacity of the AP is transferred to the area that is covered by the FRS, amounts, depending on the FRS receive antenna gain, to values between 2.6 ${}^{\text{Mbit}}\!/_{\text{s}}$ for 0 dBi gain and 18.4 ${}^{\text{Mbit}}\!/_{\text{s}}$ for 30 dBi gain. Thus, the gap between these two curves corresponds to the capacity that is inherently lost by

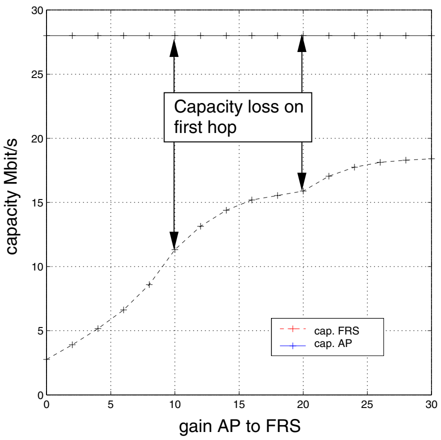
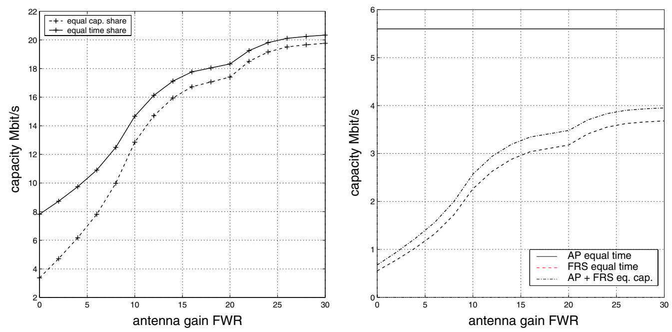


Fig. 7. Capacity of the AP in single-hop mode and capacity of FRS



(a) Difference in 2-hop-cell capacity for equal time share and equal capacity share

(b) Capacity per single infrastructure element for equal time share and equal capacity share

Fig. 8. Resulting 2-hop-cell capacity when capacity is distributed to all users of AP and the four FRSs

relaying itself.

In Fig. 8 the resulting 2-hop-cell capacity is visualized. We distinguish two ways of capacity sharing:

- **equal time share** means that the users of each infrastructure element receive the same percentage of time for transmission. As the users that are served by the AP do not require 2-hop transmission and therefore are served at a higher bit rate, they can transmit more data in their time slice. This is equivalent to the view that a lower fraction of the total cell capacity is transferred to the FRS coverage areas. As this "transmission of capacity by relaying" leads to a capacity loss, transfer of less capacity leads to a lower loss of capacity and thus the cell capacity is higher.
- **equal capacity share** on the other hand means that the time interval the users in the AP's coverage area receive a shorter time slice than the users in the FRSs' coverage areas. The duration of these intervals is adjusted to assign an equal capacity share to the users of both, AP and FRS coverage areas. This procedure is implicitely contained in Eq. (8).

The difference between these two sharing schemes is shown in Fig. 8(a).

Fig. 8(b) shows the resulting capacity *per infrastructure element* for the two different sharing schemes. In case of equal time share the AP offers a constant capacity share, while the FRSs offer a lower and variable capacity share. For the, concerning capacity per IE, trivial case of equal capacity share it is interesting to note that the FRS receive antenna gain does influence the capacity of both AP and FRS, while for equal time share only the capacity per FRS is changed by antenna gain variation.

VI. Conclusion

We have presented a simple but effective methodology to quantify the traffic capacity of cellular systems that use link adaptation. The main contribution of this new approach is that it is applicable to both the conventional one-hop architecture, and the 2-hop-cell architecture. Furthermore, it is easy to extend the methodology to cell architectures with more than one FRS in the transmission path (three or more hops).

From the viewpoint of our analysis relaying allows to transfer a part of the AP capacity from its original coverage area to the FRS coverage areas, which can be used to reach an improved coverage and resource utilization. Our method allows to quantify the fraction of the access point capacity that has to be invested for relaying. Furthermore, although due to space restrictions corresponding results have not been given, our method allows to calculate the maximum traffic offer that can be carried by a given cell configuration and for a certain user density.

We have defined two ways to organize the distribution of AP capacity over the infrastructure elements of the 2-hop-cell. While the approach of equal capacity share leads to perfectly fair service availability among all users of the cell, it has the disadvantage of a higher capacity loss. On the other hand the approach of equal time share leads to a higher total capacity, because more capacity is kept available at the AP and therefore less capacity is lost on the relaying hop. The tradeoff is that there is a difference in service quality between AP and FWR coverage areas.

References

[1] B. Walke, R. Pabst, and D. Schultz, "A mobile broadband system based on fixed wireless routers," in *Proc. IEEE International Conference on Communication Technology (ICCT'03)*, Bejing, PR China, Apr. 2003.

[2] J. Khun-Jush, P. Schramm, U. Wachsmann, and F. Wenger, "Structure and performance of the hiperlan/2 physical layer," in *Proc. 50th IEEE Vehicular Technology Conference (VTC-Fall'99)*, Amsterdam, The Netherlands, Sept. 1999, pp. 2667–2671.

[3] H. Yanikmeroglu, "Fixed and mobile relaying technologies for cellular networks," in *Proc. IEEE Workshop on Applications and Services in Wireless Networks (ASWN'02)*, Paris, France, July 2002, pp. 75–81.

[4] P. Gupta and P. Kumar, "The capacity of wireless networks," *IEEE Trans. Inform. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.

[5] 3GPP, "TR 101 112, Selection Procedures for the Choice of Radio Transmission Technologies of the UMTS (UMTS 30.03)," European Telecommunications Standards Institute, Tech. Rep., April 1998.

[6] B. Walke, *Mobile Radio Networks - Networking, Protocols and Traffic Performance*, 2nd ed. Chichester: John Wiley & Sons, 2001.