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Performance Evaluation of a Relay-Based 4G Network Deployment with Combined SDMA/OFDMA and Resource Partitioning

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***Abstract*—This work presents a low-cost, low complexity deployment concept for a relay-based cellular broadband network. The concept is based on a combination of a multi-antenna OFDMA Base Station (BS) and simple, single-antenna OFDMA Relay Nodes (RN) and User Terminals (UT). The concept further encompasses a partitioning of the available radio resources in the frequency domain to control interference within and between Relay Enhanced Cells (REC). The performance of the proposed system in a suburban cellular setup is evaluated by means of stochastic, event-driven simulation and a comparison against a pure BS-only scenario is made.[1]**

***Keywords*—4G, Relay, OFDMA, SDMA, Resource Partitioning**

I. Introduction

Relay-based radio network deployment concepts have been proposed and studied in the context of candidate technologies for IMT-Advanced systems [1]. The motivation is to enable a low cost broadband network deployment by overcoming the range-limitations of broadband air interfaces, especially at high carrier frequencies above 3 GHz. Large research initiatives like the IST-WINNER project [2] consider relays an inherent building block of next-generation wireless systems. Fixed relays for coverage and capacity enhancement are already being standardized by IEEE802.16, Task Group "j" [3] under the term Mobile Multihop Relays (MMR).

An efficient relaying concept needs to be able to support the envisaged broadband radio coverage on the one hand and allow for cost efficient relay nodes on the other hand. While increasing the coverage range through the use of relays can be accomplished relatively easy, maintaining cell capacities that can be compared to or even exceed single-hop deployments requires a careful management of the radio resources within a Relay-Enhanced Cell (REC). Transmissions across multiple hops consume more resources than a single-hop transmission. This inefficiency has to be made up for by a gain in the same order of magnitude resulting from the improved link budget on the individual hops and appropriate resource reuse strategies, both within a REC and between neighboring RECs.

Orthogonal Frequency-Division Multiple Access (OFDMA) is the prevailing transmission scheme for next-generation Radio Access Networks. OFDMA-based systems can flexibility sub-divide the available resources in the frequency-domain. Multi-Antenna solutions in combination with advanced signal processing will provide an additional degree of freedom. They enable beam forming and consequently a reduction of interference and the spatial reuse of radio resources within one cell or sector.

This paper investigates the system level traffic performance of a cellular OFDMA network with SDMA base stations (BS) and low-cost relay nodes (RN) under different static resource partitioning schemes. The investigation is performed by means of stochastic, event-driven simulation in a multi-cellular scenario. The remainder of the paper is organized as follows: The next section discusses previous and related work. Section III presents the deployment and the considered resource partitioning schemes. Section IV gives details on the system model and the simulation scenario. Section V presents the simulation results while Section VI concludes this work.

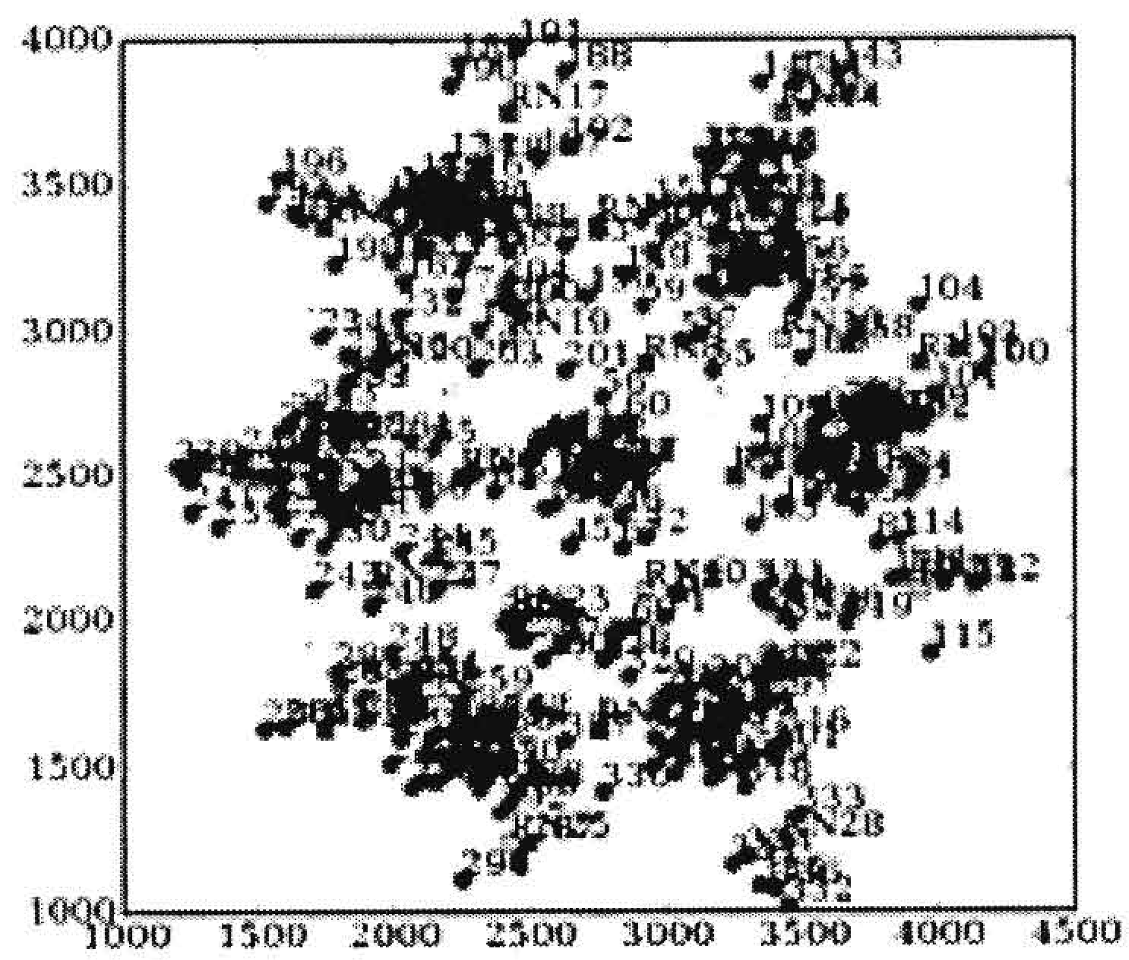

Fig. 1. Multi-Cellular Wide-Area deployment with 44 UTs (green circles) per REC in a wide-area setup. 3 RNs (red, green, yellow squares) per BS (blue triangle)

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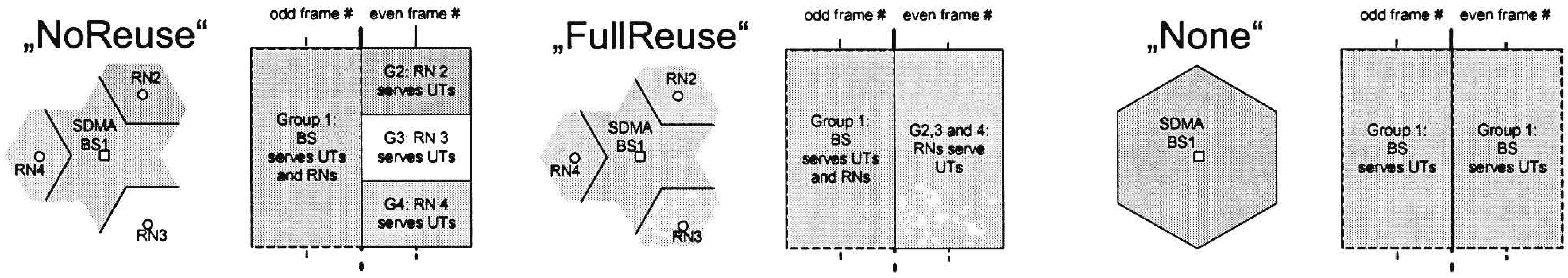

Fig. 2. Considered resource partitioning examples. Left: Concurrency of Relay Links and first hop Access Links / full separation of second-hop access links, middle:: same as left, but with full frequency reuse in all relay-subcells, right: single-hop comparison case - all resources used by BS.

II. Related Work

Static, load-based resource partitioning is intended to provide a cost-efficient yet flexible solution to partition resources in REC-based deployments. Cost-efficiency is targeted through low hardware requirements of the RNs while the possibility to periodically re-arrange the partitioning offers the required flexibility. While [4] does not consider relay-based deployments, the authors have provided a comprehensive comparison of inter-cell resource partitioning in the time- and frequency-domain. In our work, only a partitioning in the frequency domain is considered. The reason for this is that in the targeted wide-band system concept, even after the subdivision, sufficient frequency diversity is retained (>20MHz spacing of frequency resources). The authors of [5] investigate the same system concept as in this work. However, more complex (i.e. multi-antenna) relay nodes and a dynamic partitioning scheme that relies on these advanced signal-processing capabilities make the results difficult to compare. An overview about the resource-partitioning-related efforts of the IST-WINNER project can be found in [6].

III. Deployment and Resource Partitioning

The target of the proposed static partitioning is to provide a low-cost solution with low hard-ware requirements put to the relay nodes. The envisaged deployment is characterized by: (a) Single Antenna (Omni directional) Relay Nodes, (b) Single Transceiver Relay Nodes (Relaying/Forwarding is performed in the time domain) (c) Smart Antenna Technology at the BS only, to keep RN equipment cost low.

We investigate a regular, hexagonal deployment covered by two-hop RECs. Each REC consists of one BS and three RNs. Both BSs and RNs are referred to as Radio Access Points (RAPs). From the perspective of the user terminal, there is no difference in being connected to either or the other of the two RAP types. As a worst-case assumption this work considers a reuse factor of one between adjacent RECs. This means the possibility of full inter-cell collision is inherent to all investigated schemes.

The system's available time-frequency resources are assigned to so-called groups of RAPs, where - in the extreme case - each RAP node belongs to a distinct group while - in the other extreme - all RAPs could belong to the same group. The groups are used for intracell frequency planning by the partitioning scheme – RAPs belonging to the same group may reuse the same resources. In order to exploit the resources within a REC as efficiently as possible, one can try to identify RAPs within the REC that are sufficiently well separated from each other (in terms of path loss/shadowing) to enable re-using the same resources. In the case of centralized resource partitioning schemes, the groups may also be used for intercell frequency planning.

The optimal fragmentation of resources within a REC also highly depends on the distribution of the users, i.e. of the distribution of the offered traffic load within the REC.

As a starting point, this work assumes a relatively homogeneous traffic distribution and therefore an even distribution of resources (see Fig. 2).

The overall spectral efficiency of a relay based deployment is expected to highly benefit from a spatial reuse of the resources, not only between different relay subcells as outlined above but also on the relay link. It is therefore envisaged that the BS uses SDMA based on beam forming to feed the RNs and the User Terminals (UTs) on the first hop. In addition a careful placement of the RNs with respect to the BS is considered and thus yields maximum spectral efficiency on the relay links.

IV. System Model

Most of the assumptions of the system model closely follow the suggestions made by the IST-WINNER project in [7]. A selection of important aspects required to understand the simulation results will be given in this section.

A. System Characteristics

The Medium Access Control (MAC) super frame structure of the investigated system is shown in Fig. 4. Each super frame consists of 8 MAC frames. Relay Nodes alternatingly behave as UTs towards the BS and in the subsequent frame behave as BSs towards the UTs in their respective sub-cell.

The available physical resources have been divided into Resource Allocation Units (RAUs) according to the proposal in [7] for non-frequency-adaptive transmission (see Fig. 3). This results in 18 parallel, mutually interleaved frequency subchannels, each of which comprises 64 OFDM-subcarriers and spans approximately 20 MHz to provide sufficient frequency diversity. Each RAU spans 3 OFDM symbols in the time domain. Consequently, a RAU provides 192 Symbols. Each MAC frame spans 24 OFDM symbols, the first three of

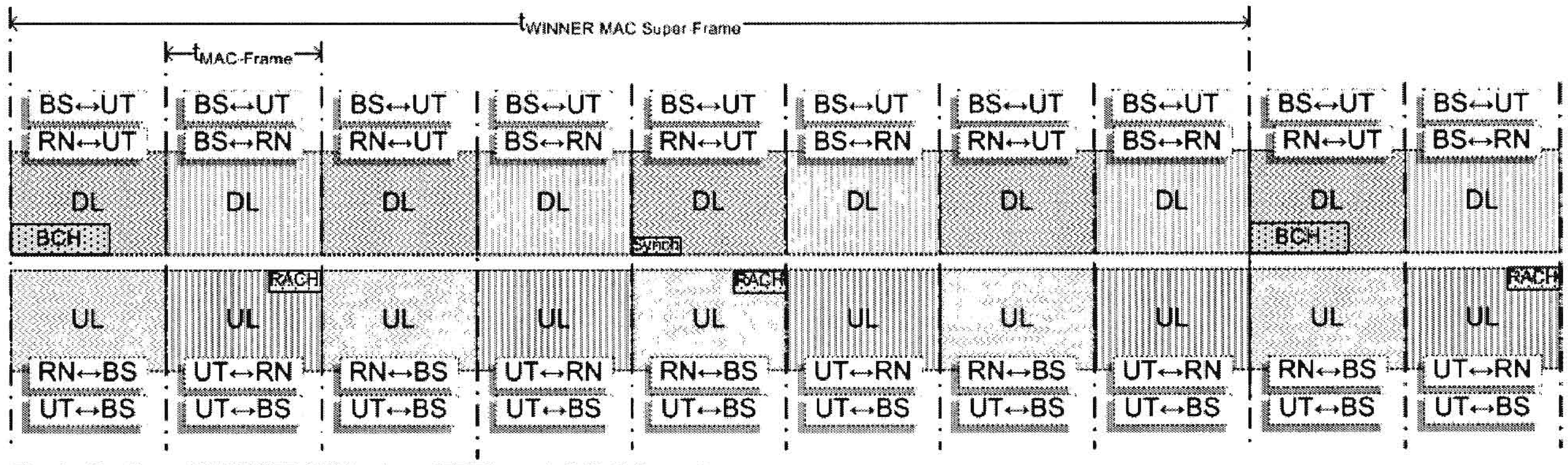

Fig. 4. Outline of WINNER Wide-Area (FDD) mode MAC SuperFrame

which (=12.5%) are accounted for as frame organization overhead

The spatial grouping at the base station is performed according to a tree-based algorithm applying a DoA-heuristics as described in [8]. The DL scheduling is following an Exhaustive Round Robin strategy. Spatial groups of up to 4 parallel users are scheduled at the BS and individual users are scheduled at the RNs. An additional feature is that RNs and UTs are grouped into distinct groups to be able to fully exploit the good channel conditions on the relay link and to account for different amounts of traffic for RNs and UTs without causing scheduling inefficiencies caused by unbalanced groups.

Link Adaptation was performed based on averages of received power and interference levels, taking into account the expected beam forming gains. A fixed code rate of ½ and no additional puncturing was assumed. The modulation was chosen according to the SINR prediction and switching thresholds were obtained from Fig. 5 The Link-Level Mapping was performed using a Mutual Information-based approach described in [9] and based on a Linear Density Parity Check (LDPC) code with ca. 2000 bit code word length.

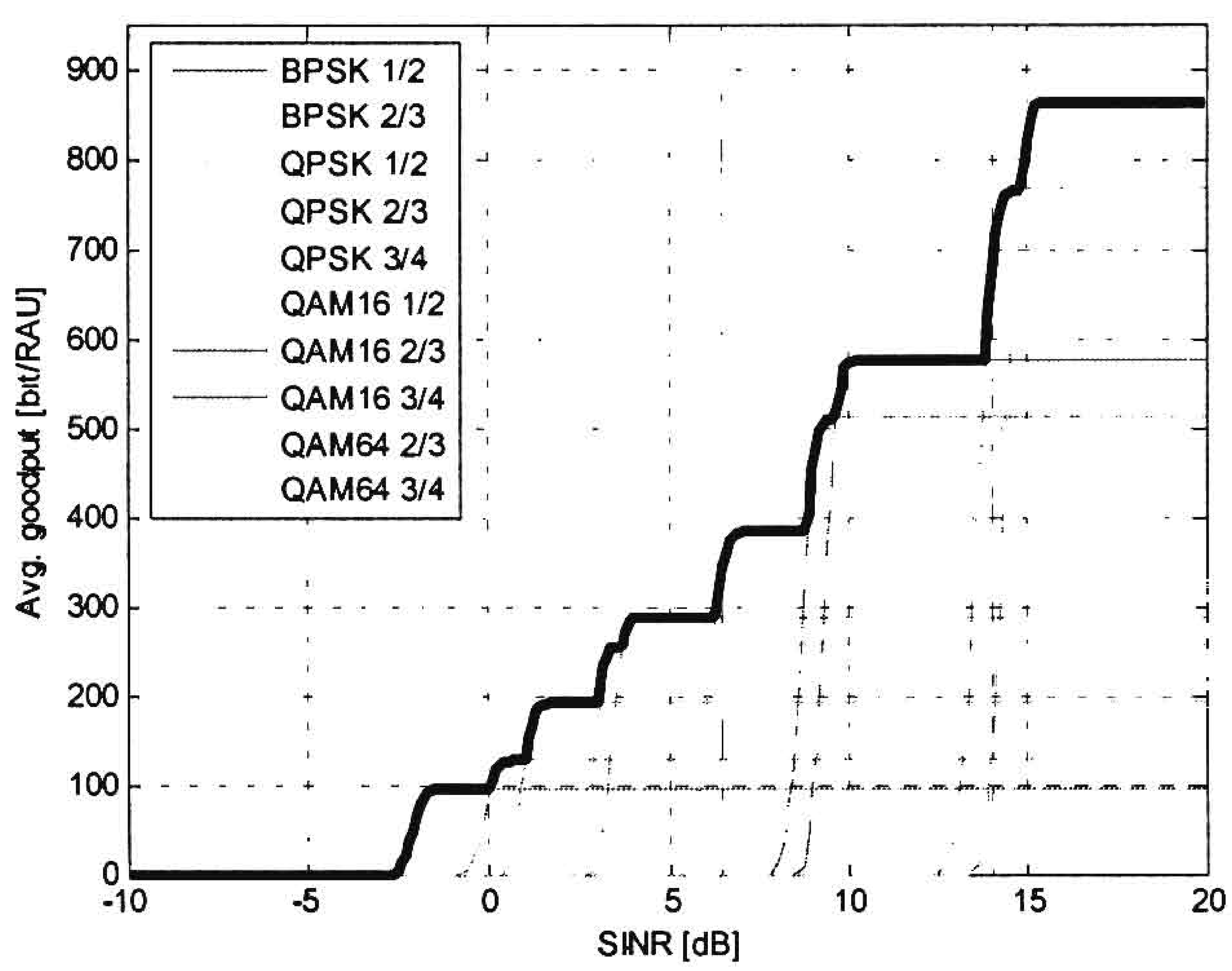

Fig. 5. Performance of Modulation and LDPC Coding schemes (average goodput in bit/RAU vs. effective SINR)

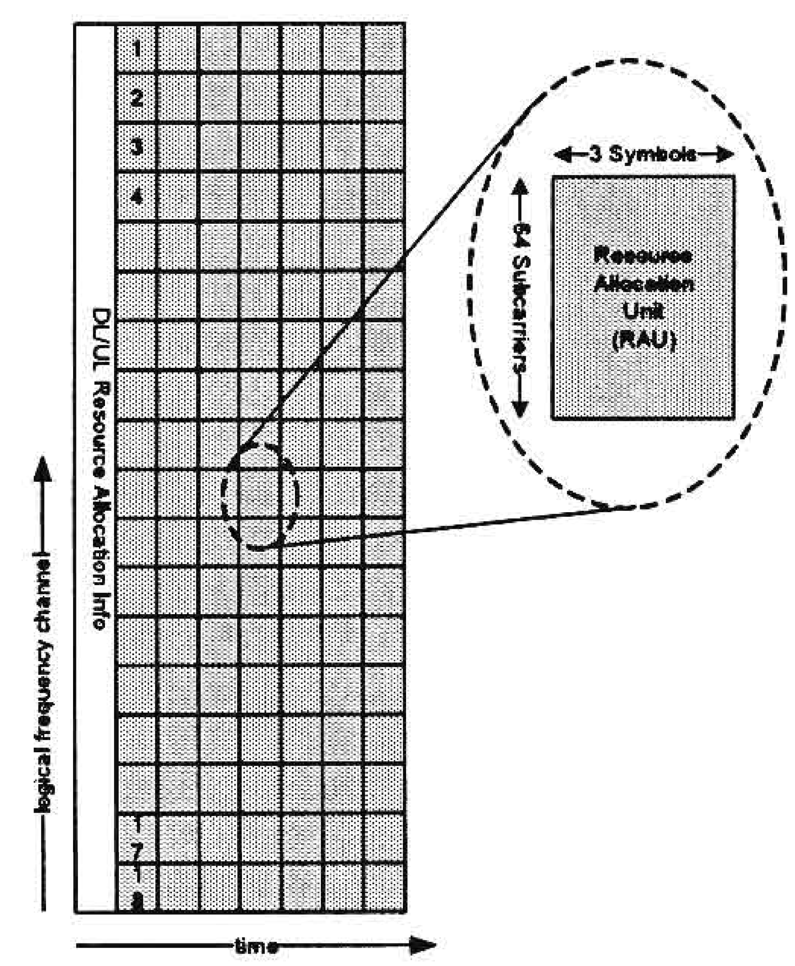

Fig. 3. Resource Allocation Units and reserved signalling overhead (12.5%) in the FDD frame structure.

The propagation models applied in the simulations were chosen in view of a planned deployment of the RNs, i.e. it was assumed that favorable channel conditions between the BS and the RN would be the result of a deliberate RN deployment. The used channel models are taken from [10]. Whether LOS or NLOS conditions were assumed between different station types can be found in Table I.

The scenario has been investigated for different deployment densities. The distance *d* between BSs has been set to 800m, 1000m and 1200m, respectively. The distance between BS and RNs has always been 45% of the BS-BS distance, placing the RNs relatively close to the cell edge.

TABLE I

OVERVIEW ABOUT APPLIED PROPAGATION MODELS

Relation	Model	LOS/NLOS
BS ←→ RN	C1	LOS
BS ←→ RN (interferer link)	C2	NLOS
BS ←→ UT	C2	NLOS
RN←→ UT	B1	LOS
RN←→ UT Interferer link	B1	NLOS

B. Resource Partitioning

Fig. 2 shows the two exemplary resource partitioning patterns investigated in this work.

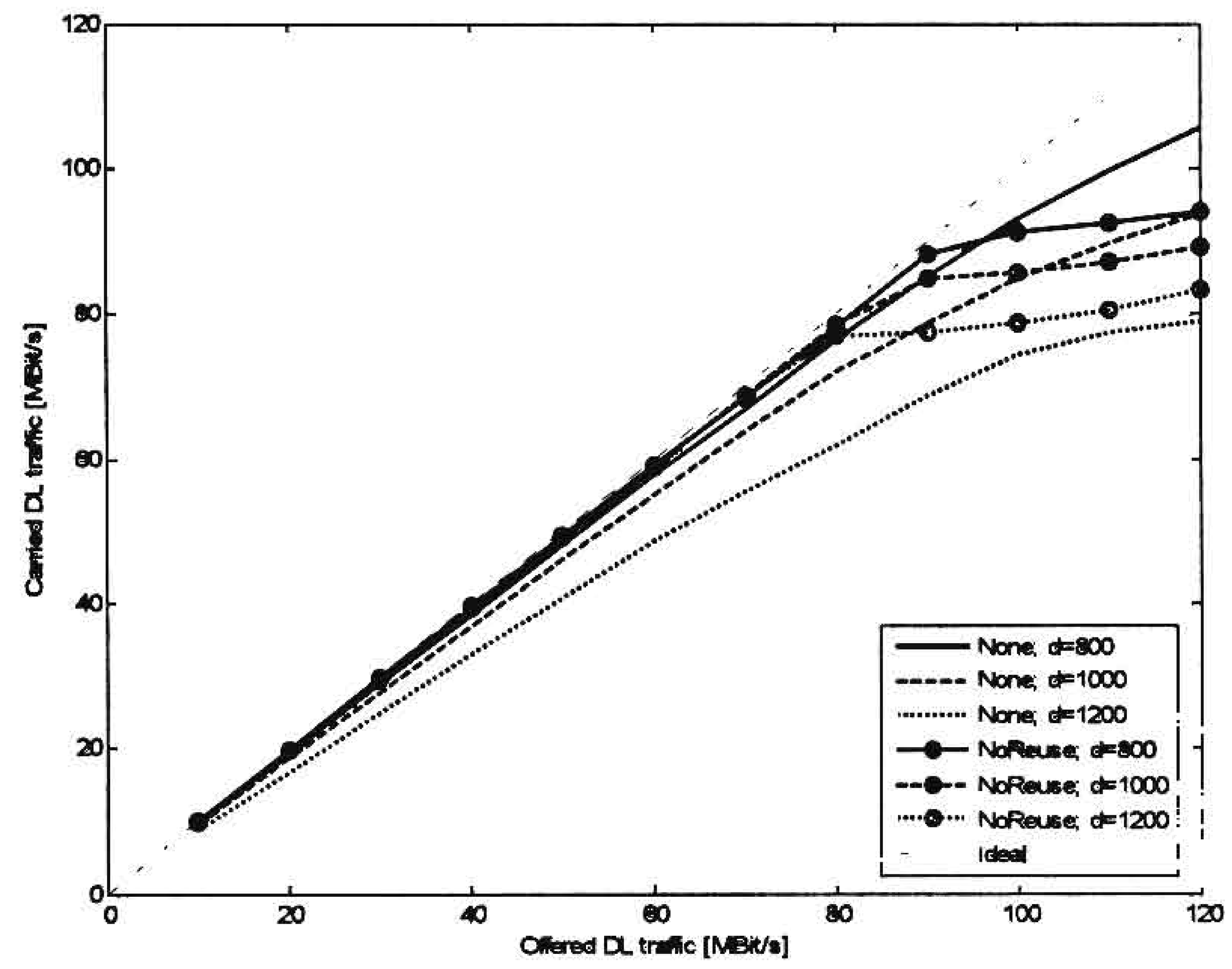

Fig. 6. DL Cell Throughput in the center cell vs. offered DL traffic

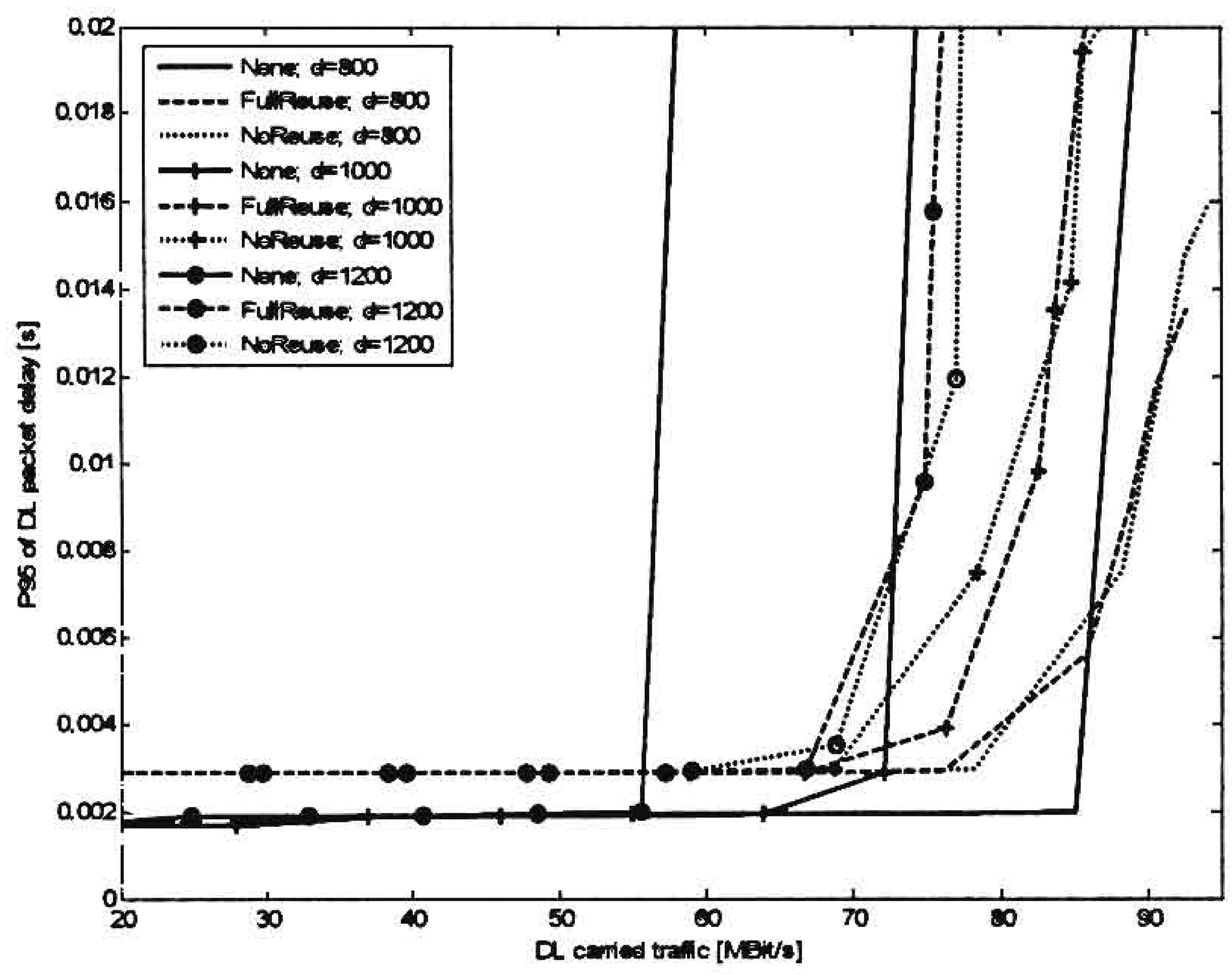

Fig. 7. 95th Percentile of DL packet delay vs. center cell throughput

The scheme labeled *"No Reuse"* suppresses intra-REC interference between RN subcells by assigning individual resources to each of them. All RNs serve as RAPs in the same frame and all resources are evenly shared among them. During the frame where the RNs are active in their RAP role, the BS will remain silent. Corresponding RNs in neighboring RECs will re-use the same resources.

The scheme labeled *"Full Reuse"* presents the opposite extreme case in that it permits parallel resource usage in all RN subcells of a REC, leading to higher intra-REC interference between RN subcells, but allowing higher diversity and a trunking gain owing to the larger number of available frequency channels.

A traditional, hexagonal single-hop scenario labeled *"None"* is used as a comparison case. Again, it implements a reuse factor of one between neighboring cells.

TABLE II
OVERVIEW ABOUT SIMULATION PARAMETERS

Parameter	Value
Carrier frequency	3.95 GHz DL 3.7 GHz UL
Channel bandwidth	2x50 MHz
Number of cells	7 (center evaluated)
Users per cell	44 (26 One-Hop, 18 2-Hop)
Inter-site deployment	800m, 1000m, 1200m
Distance BS - RN	45% of distance BS-BS
Traffic load	DL only, 10-120 MBit/s, individual arrival processes per user
BS number of antennas	11 (Uniform Circular Array)
RN number of antenna	1
UT number of antenna	1
BS transmission power	46 dBm
RN transmission power	37 dBm
UT transmission power	24 dBm
Traffic model	Full buffer
Retransmissions (ARQ, HARQ)	No
Segmentation and Reassembly	No
Link adaptation	Yes
Mobility	No
Resource scheduling	Exhaustive Round Robin (RR)

C. Traffic modeling

User data traffic has been modeled according to a per-user Poisson arrival process (neg. exp. Distributed packet inter-arrival times). All simulations were run with a fixed number of 44 Users per REC. Scaling of the overall traffic load per cell has been performed by scaling each user' share of the traffic. Example: At 50 Mbit/s cell load, each user has an individual offer of 50e3 / 44 = 1.136 MBit/s. At a fixed packet size of 128 byte, this corresponds to an average of 1110 packets per second and user.

User terminals within the area of a REC are evenly distributed in circular areas around each RAP (see Fig. 1). As an exemplary distribution, the 44 UTs in the cell were divided into 26 UTs immediately connected to the BS and 18 UTs connected via the 3 RNs (6 each). In the single-hop comparison case, all 44 Users were connected to the BS immediately but remained in the same positions as in the multi-hop simulations.

In the case of bottlenecks, all nodes can drop packets when their buffer capacity is exceeded. BS and UT have "outgoing" buffers while the RN has a "forwarding" buffer.

V. SIMULATION RESULTS

The goal of the simulations is to provide an estimation of the performance of the WINNER protocol in Wide-Area mode under the following assumptions:

- different static resource partitioning settings
- non-full buffer traffic and finite buffer-capacity at all nodes
- SDMA group scheduling at the BS

Fig. 6 shows the DL sustained REC throughput vs. the total offered DL traffic. The relay deployment (only *"NoReuse"* shown for simplicity and because it performed slightly better than *"FullReuse"*) improves coverage as the performance at low traffic loads shows With increasing cell size, the BS can

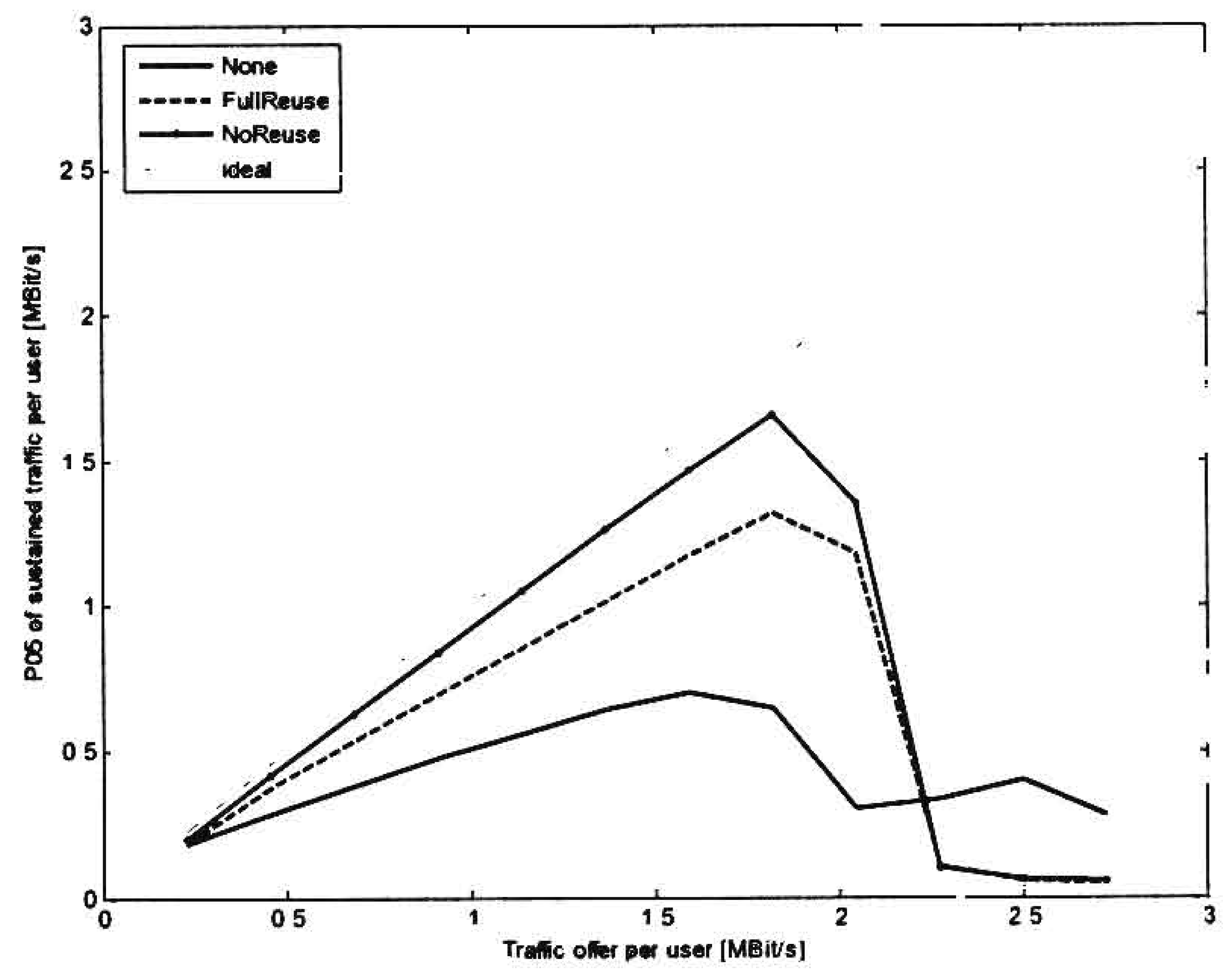

Fig. 8. 5th Percentile of DL individual user throughput vs. offered DL traffic per user

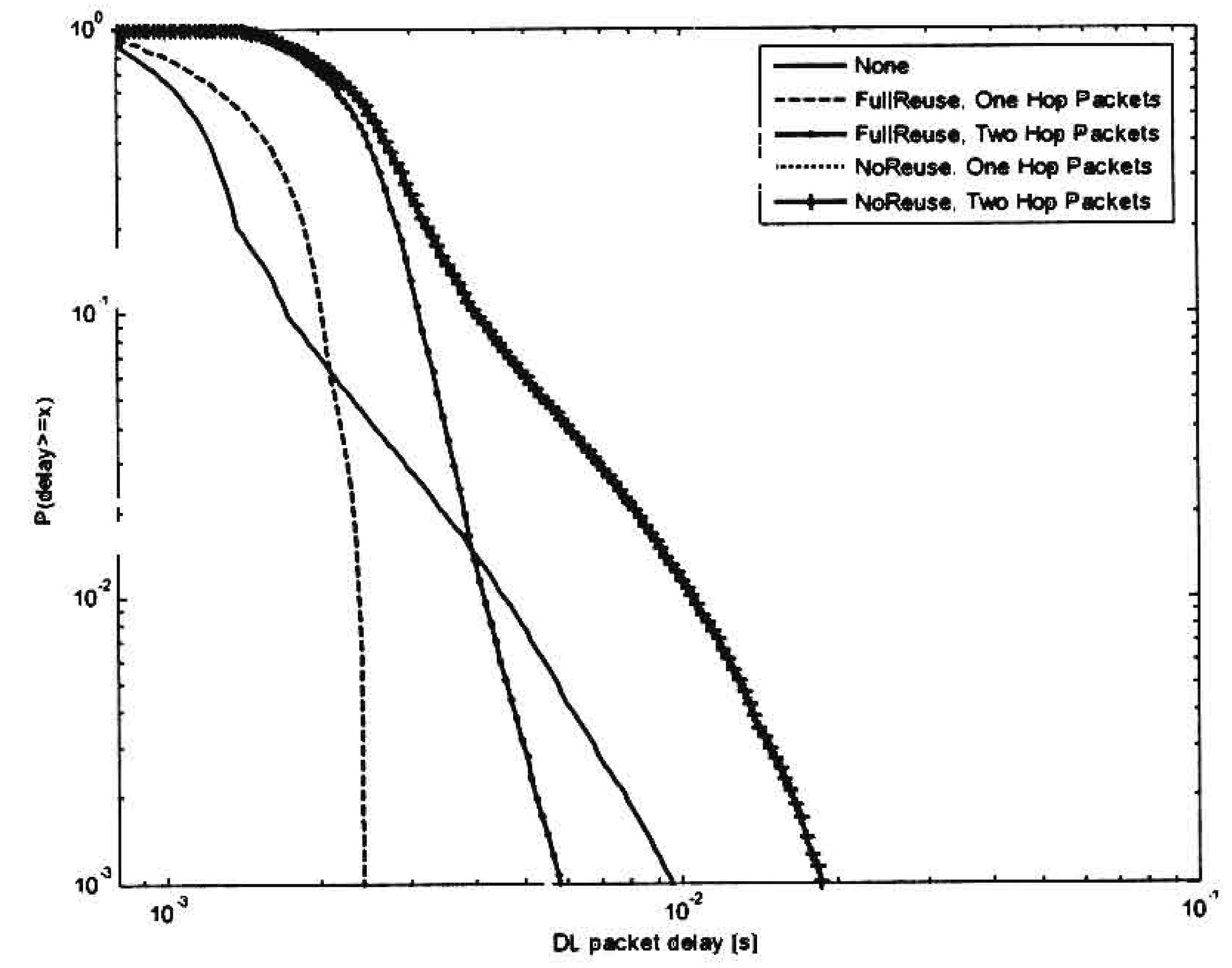

Fig. 9. CCDF of DL Delay for One- and Two-Hop data packets at a DL traffic offer of 80Mbit/s and a site-separation of 1000m

not serve all users, leading to a discrepancy between offered and sustained traffic already at low loads. On the contrary, the relaying deployment delivers stable coverage and - in the case of larger cells - higher saturation and peak throughput than the single-hop solution. At 1200m inter-site distance, a cell throughput of about 80Mbit/s is achieved.

Fig. 7 indicates the achieved Quality of Service. It plots the 95th percentile of the DL Packet Delay versus the sustained DL traffic. Naturally, in low load cases the BS-only deployment exhibits ca. 30% shorter delays than the relay-based deployment. However, all relay-based cases show a less harsh saturation behavior and overall higher saturation throughput than the respective single-hop cases. At e.g. 1200m site separation, the relay deployment improves the saturation throughput from 55Mbit/s to more than 70Mbit/s, i.e. by more than 25%.

Figs. 8 and 9 illustrate the individual user experience. Fig. 8 shows the 5th percentile of the individual user's received DL throughput vs. the offered traffic per user. This means that 95% of all users achieve a DL data rate higher than the given figures. It can be seen that the introduction of relay nodes improves user satisfaction and inter-user fairness substantially. The *"NoReuse"* partitioning seems to perform best in this discipline. Fig. 9 plots the Complementary Cumulative Distribution Function (CCDF) of the DL packet delay at an exemplary traffic offer of 80MBit/s. Where applicable, the figure distinguishes between users which are immediately connected to the BS (One-hop) and those which are connected to RNs (Two-hop). The smaller amount of resources available on the second hop notably increases the delay for two-hop users. It also shows that the two partitionings compared do not differ in terms of delay on the first hop, since the first-hop resources are the same in both cases (cf. Fig. 2).

VI. CONCLUSIONS

We have shown a concept for a low-cost, low complexity deployment of a relay-based cellular broadband network in suburban scenarios. The concept is based on a combination of a smart-antenna OFDMA BS and simple, single-antenna OFDMA RNs and UTs. The concept further encompasses a partitioning of the available radio resources in the frequency domain to control interference within and between RECs. Simulation results have shown that the relay-based deployment substantially improves the level of coverage and the network capacity. From a QoS point of view the simulations have shown that in the given scenario, the partitioning which provides protection against intra REC interference exhibits the best performance. To assess the validity of this statement, future work will investigate the influence of varying distribution of users in the area of the REC.

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