On OFDMA FDD mode in 3G-LTE

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***Abstract*— New generations of cellular radio systems are currently being developed based on OFDM transmission with OFDMA as the multiple access scheme. The demand for high data rates in reasonably large areas is omnipresent, but the conventional cellular architecture offers does not only a maximum rate depending on the distance. Close to the base station, the higher received $SINR$ valueallows the highest Modulation&Coding scheme (PhyMode), which offers the highest data rate. In this paper we user the mutual information approach to calculate the maximum data rate based on the $SINR$ at all positions in an interference-limited radio cell.**

Near the cell border the offered data rate is one order of magnitude lower. Relaying or Multihop operation is an option to massively improve the coverage as well as the capacity issue at low cost, without the need of a cable or fibre access. In this method, the base station coordinates the partitioning of radio resources within the *relay enhanced cell (REC)*. Frequency division duplex (FDD) is preferred for large area coverage and is the preferred mode for the beyond-3GPP project LTE [1]. The OFDMA multiple access scheme allows the base station (BS) to transmit to several user terminals (UT) at the same time, in distinct subcarriers. The principle coordination tasks of OFDMA resources in the singlehop and multihop case are discussed. Using an analytic framework in Matlab, we obtain performance results to show the radio coverage in a REC in terms of maximum data rate over the area. [1]

I. Introduction

Multihop capable air interfaces are becoming more and more interesting due to their improvements of coverage and capacity. For that reason they they are proposed for the next generation cellular systems like 3G-LTE [1]. The maximum data rate offered by a base station depends on the distance of the mobile to the base station. Close to the base station, the higher received $SINR$ value[2] allows the highest Modulation&Coding scheme (PhyMode $64QAM-5/6$), which offers the highest raw data rate of approximately $100Mbit/s$. At the cell border and in significant fractions of the cell area, the offered data rate is one order of magnitude lower. What makes this even worse is that some terminals operating at the lowest PhyMode occupy a ten times bigger part of the spectrum than the same number of terminals operating at the highest PhyMode. That means the average cell capacity is overproportionally determined by the maximum possible rate at the outer regions. Figure 1 gives an idea of this problem.

By using relays (relay nodes, RN) positioned near the cell border the coverage can be extended significantly, assuming that the stationary link between RN and BS has a low pathloss due to close to line-of-sight propagation or higher antenna gains. By positioning a relay within the classical cell boundaries the capacity of an area around the RN is also increased. Figure 2 shows the two ways from a conventional cellular layout to multihop-augmented cells for both goals.

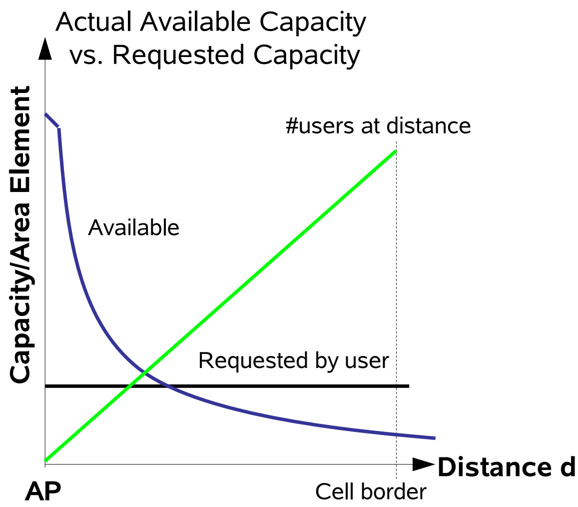

Fig. 1. The single hop problem: With a constant user density the number of users increases with d, so the cell capacity offered per area element differs from the capacity requested by users

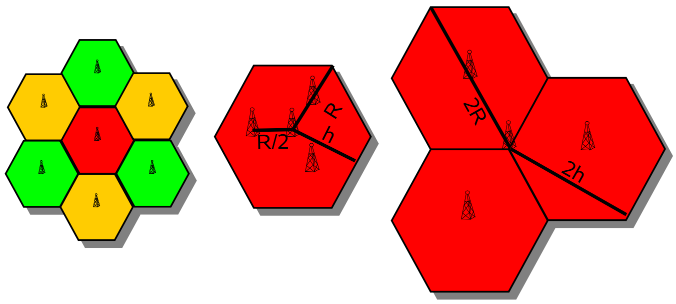

Fig. 2. Left: Conventional cellular geometry, Middle: Best geometry to increase capacity, Right: Best geometry to increase coverage

The paper is organized as follows. The first section discusses the FDD OFDMA topic. Then, the analytical model is explained. The last section deals with performance results.

II. The FDD mode with OFDMA

OFDM has evolved as an efficient multiplex scheme of typically 1024 small orthogonal subcarriers within the system bandwidth. Small subcarriers mean long symbols in time, so the problem of inter symbol interference (ISI) is relieved. The big advantage of OFDM is that each subcarrier can be modulated differently, so a robust BPSK can be used on

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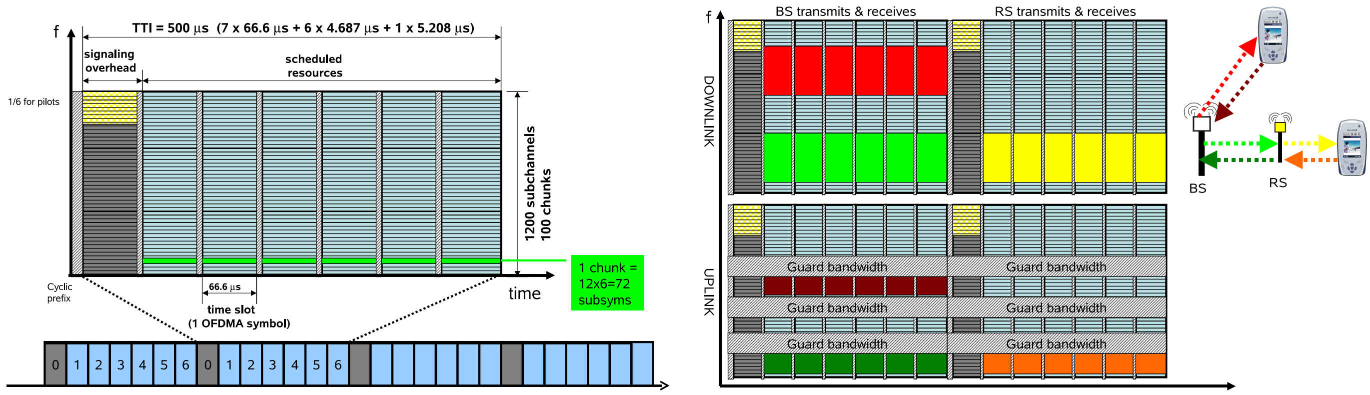
[2]$SINR = signal/(interference + noise)$, a measure for the quality of the transmission in [dB].



(a) One Downlink TTI frame

(b) DL and UL frames for relaying

Fig. 3. Frame format for OFDMA transmission. This example shows one TTI frame ($500\mu s$) for 3GPP-LTE [1]. On the right, a dynamic resource allocation for a relaying scenario is shown.

frequencies where the channel is currently bad due to fading, while e.g. QAM64 can be used on more stable subcarriers with higher $SINR$ values. Channel coding is also adjusted in wide ranges to adapt to the subchannel conditions. This is called dynamic adaptive modulation and coding (AMC) [2]. Modern OFDMA can also allocate a higher power level to those subcarriers for the distant UT, as long as the total power is below its regulatory limit. This Adaptive Power Allocation (APA) is quite a new idea for OFDMA.

OFDM**A** means that within one OFDM symbol, several different UT receivers can be addressed. So for example, 256 subcarriers are used for each of four UTs that receive the symbol. Dynamic subcarrier assignment (DSA) selects the best resources for each UT based on channel state information (CSI). As the distance and pathloss may be very different among the UTs, it is likely that the PhyModes used for each UT are very different within the full OFDM symbol.

A. Orthogonal Resources

Radio resources are the valuable goods that nobody can get enough of. Traffic and tariffs are typically proportional to the used or allocated resources of a user. The shannon bound limits the number of bits that can be transmitted in a given resource block of frequency (bandwidth) and time (transmission duration) given a certain $SINR$ situation. In OFDMA, the granularity of these resources is typically a *chunk*, i.e. a group of subcarriers if f-direction and a number of OFDM symbols in t-direction. Figure 3(a) shows the downlink frame format proposed for 3GPP-LTE [3]. A chunk of size 12 subcarriers times 6 symbols can carry up to 360 bits in PhyMode $64QAM - 5/6$. Smaller resources with finer granularity could fit smaller traffic better, but the overhead for segmentation, signaling and control increases to inefficience. An obvious additional resource dimension is space. Resources used at one location (cell) can be reused at another place (see reuse distance 3 in figure 2 left).

B. Differences in Downlink and Uplink

Using OFDMA on the uplink sets up a new problem. In contrast to OFDM, where one sender occupies the full bandwidth, OFDMA could allow several senders to occupy non-overlapping parts of the bandwidth. But then the orthogonality of the symbol is no longer guaranteed by construction. It is currently hard to imagine a fully synchronized coherent transmission of UTs. There are different locations, different power levels, different timing and RF phase, and even mobility which leads to differences in Doppler shift. Until proof of feasibility the assumption of uncorrelated senders must hold. Therefore a guard band of some unused subcarriers is needed between resources from different UTs to protect the useful signal power from the interfering side-band transmission power of neighbour frequencies. The *adjacent channel leakage ratio* (ACLR) characteristic of narrow OFDM transmissions needs to be taken into account here. In figure 3(b) these uplink guard bands are illustrated.

III. Multihop Operation

So far the orthogonality of resources helps assigning non-interfering blocks to each UT and RN. The duplex mode decision, i.e. how to separate uplink from downlink traffic, is just another use of orthogonality. For time division duplex (TDD), downlink and uplink phases alternate periodically, for example in the Winner system [4]. In Multihop mode, this frame is not changed for a single hop. The only difference to singlehop is that from time to time, a complete frame is allocated to the second hop, so that the packet transport over the wireless loop has four phases for which it takes four frames: $BS \rightarrow RN$, $RN \rightarrow UT$, $UT \rightarrow RN$ and $RN \rightarrow BS$. All 4th generation systems can use this method for relaying, as the interference-free allocation of resources is centrally controlled by the BS.

A. Frame Formats for FDD with Relays

TDD relaying is known field, so good solutions exist [5]. For relaying, the FDD mode does not differ much, except the missing guard times and parallel transmissions in downlink and uplink.

The BS always sets up the master frame, i.e. generates the timing schedule for the next period. Beginning with

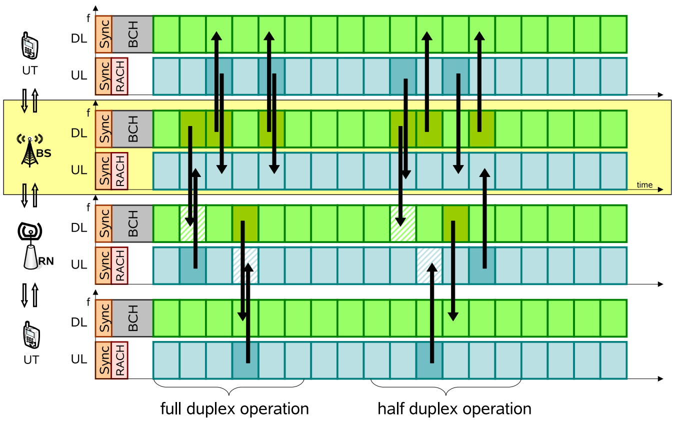


Fig. 4. Radio Frame format for FDD operation. Frame at BS: Base Station sends in downlink and receives in uplink resources. Top and bottom frame: User Terminals send in uplink and receive in downlink resources. Frame 3: Relay Node has transceivers that can send+receive both in UL and DL

synchronisation pilots, a broadcast channel (BCH) and a random/contention access channel (RACH), a number of regular frames follow which depend on the technology. The BS also reserves some of the frames for the second hop(s), to be used in the responsibility of the relay(s). With *stealth relaying*, the BS does not even distinguish between relays and ordinary UTs, However, a centrally and relay-aware BS controlled resource allocation is preferable in all cases for future systems. Modern multihop systems incorporate interleaved multihop frames, where frames for the first and second hops alternate in time, all controlled by the BS.

The smallest granularity resource unit is a chunk, and 100 of them fit into this basic frame. Symbols used for signaling and synchronization are out of focus here (shown in grey in figure 3(a)) and the only impact here is the overhead (resources not available for data throughput). Downlink and uplink transmissions happen simultaneously in the same frame raster. There are three ways to integrate relaying, i.e. the frames used for the second hop (or beyond):

- **Time Domain Relaying:** resources for $hop1$ and $hop2$ are separated in time (sequentially)
- **Frequency Domain Relaying:** resources for $hop1$ and $hop2$ are separated in frequency (neighbour band)
- **OFDMA Domain Relaying:** resources for $hop1$ and $hop2$ are separated in frequency (subchannels)

Frequency Domain Relaying is trivial. It simply means we need another center frequency for the second hop. Then the BS doesn't need to reserve extra (idle) frames. It treats RNs as UTs. And the second hop acts as if it was a standalone cell. The result in performance is the same as for a wireless feeder. The main drawback is the higher usage of spectrum, i.e. a reduced spectral efficiency of the system.

B. Time Domain Relaying

For a normal singlehop transmission (upper terminal in figure 3(b)) the BS uses dedicated resources on the downlink channel which it can allocate for itself, knowing the traffic demand. Transmissions towards the RN happen in the same frame, just like to any other terminal. The traffic is known as well because the downlink scheduler knows the number of packets in its queues.

Power control can be used to assign a different transmit power to both blocks; the station closer to the BS doesn't need the full power compared e.g. to an UT at the cell border. Because of the FFT operation for OFDM, the full DL bandwidth is in use by the RF backend of the BS. For the second hop DL transmissions, the RF sender of the RN is active. Because RN and BS are hard to synchronize, especially for the required OFDM orthogonality, all the power of the other sender must be treated as side-band interference. So the transmission must happen in a separate frame to avoid interference and the BS must reserve the complete resources of this frame for the second hop.

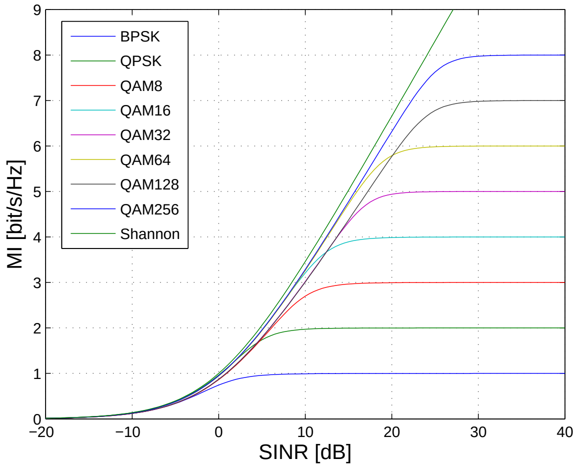
The frame schedules at BS,RN,UT1,UT2 for a small scenario is shown in figure 4. In the downlink direction either the BS sends to UTs and RNs, or the RN uses this time slot. The uplink is simply used in parallel at the same time, but this is not necessarily required. For duplex and simplex FDD UTs, the schedule is different. On the right of figure 4 is shown that for simplex terminals the send and receive phases must not happen simultaneously. Without the need for a duplex filter, simplex allows for cheaper radio hardware.

C. OFDMA Aided Relaying

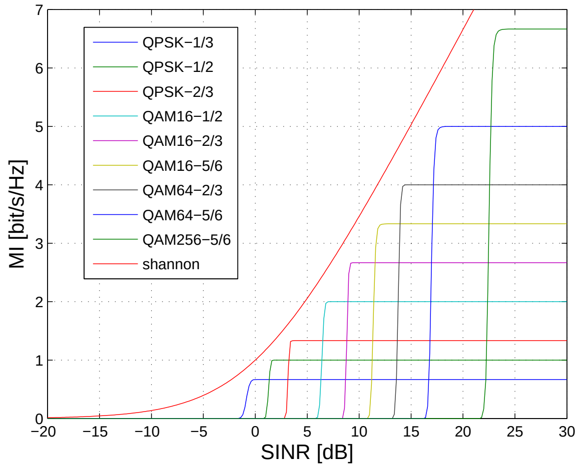
With OFDMA there are some additional benefits for relaying: The resources can be subdivided in a finer granularity than what would be possible with OFDM only. Figure 3(b) shows that first-hop transmissions are all treated the same way. They just occupy the required resources for their traffic. There is no waste due to completely assigned but incompletely filled frames. In the uplink also several UTs share the full bandwidth, each of them transmitting on a subset of subchannels, with a guard band between them. The BS or RN coordinates the orthogonal interference-free use of these subchannels by the UTs. There can also be OFDMA subdivision in the downlink, such that BS and RNs send on distinct subchannels, with a sufficient guard band. Even if the side band power (see section II-B) is $-20dB$ below the signal level, this can cause serious interference trouble at the UT when receiving the useful signal from a far distant BS and the interference from the RN nearby. Helpful are interference mitigation strategies in the BS. This leads to proper association decisions for intra-cell handover.

IV. Performance Analysis

The coverage extension scenario for relaying (fig. 2) has been investigated. An analytical/numerical analysis of cellular systems has been performed using Matlab. For simulative analysis we use the WNS simulator [6]. With the simulation model it is possible e.g. to account for a traffic $load < 100\%$, detailled timing, resource coordination, interference mitigation and QoS scheduling. Simulation results can be found in [7].



(a) Mutual information (MI) depending on $SINR$ and PhyMode



(b) resulting net rate taking PER and ARQ into account

Fig. 5. Link level results for different modulation&coding schemes (PhyMode). They are calculated analytically, not by simulation.

A. Analytical Model

The following steps were taken to get the MAC layer throughput:

- *Transmit Power:* $40W_{peak}$ at the BS,
- *Pathloss I:* non-line-of-sight propagation,
- *Pathloss II:* slow and fast fading effects,
- *Interference:* neighbor cell BSs interfere (100% load, cluster order $C = 7$),
- *Noise:* accounted for but not serious in interference-limited systems,
- *SINR:* the first performance measure below PHY layer,
- *MI:* mutual information [8] determined from $SINR$ and modulation as described in [9],
- *BER:* bit error ratio, the PHY performance result, depends on the Channel coder used,
- *PER:* packet error ratio, the result after channel decoding ($PER = 1 - (1 - BER)^{N/bits}$),
- *Delay:* determined by PER (ARQ retransmissions) and roundtrip times ($d_{aboveARQ} = T_{frame} \cdot (1 - PER)^{-1}$),
- *Throughput:* determined by bandwidth, PhyMode (modulation and code rate) and ARQ overhead ($r_{aboveARQ} = r_{belowARQ} \cdot (1 - PER)$).
- *Second Hop Throughput:* reduced by resources required on first hop ($r_2 = (r_{1,max}^{-1} + r_{2,max}^{-1})^{-1}$).

For the $SINR$ to MI translation we use the new analytic formula [9]:

$$MI(SINR, m) = \frac{1}{([s \cdot MI_{shannon}(SINR)]^{-w} + m^{-w})^{1/w}} \quad (1)$$

using the following abbreviations

$$MI_{shannon}(SINR) = log_2(1 + 10^{SINR/10dB}) \quad (2)$$

$$s = s(m) = 0.95 - 0.08 \cdot (m \bmod 2) \quad (3)$$

$$w = w(m) = 2 \cdot m + 1 \quad (4)$$

Here m is the modulation index, i.e. the number of bits per symbol (1=QPSK,...8=QAM256). See figure 5(a) for the result of equation 1.

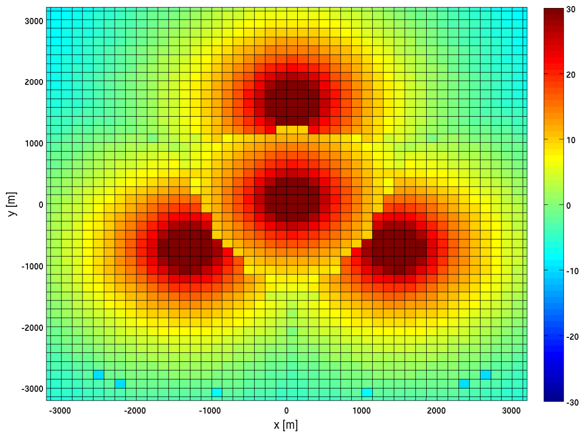
B. Coverage analysis result

Figure 6 shows results for the coverage extension scenario defined in fig. 2. The DL SINR results plotted over the cell area show the $SINR$ of the best station (BS,RN), not the maximum $SINR$. The important difference is that the *best station* (fig. 6(c)) is determined by the highest rate any of the stations can offer. The rate/throughput results contain the maximum achievable rate at a certain position within the cell, taking also the required first hop resources into account. Therefore, the second hop maximum rate near the relay cannot be as much as near the BS. The relay is chosen as the serving station (association) if this is an advantage in less resources used, which is here the same as the maximum rate. In both scenarios there are huge areas where the relay offers an advantage over the singlehop case. So there is more than just high $SINR$ around RNs.

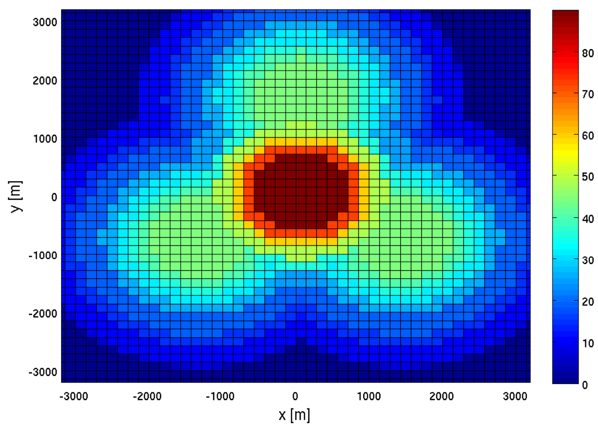
The cell geometry is extended as shown in figure 2 so that the covered area is three times the original area (+200%). In figure 6(a) the area served by the BS is small compared to the coverage achieved by the relays. Figure 6(d) shows that the maximum rate around the RNs is only half of the BS rate, but in areas the BS would never cover. So while the inner cell still has capacity to offer, it can be used to extend the coverage very economically.

V. Conclusion

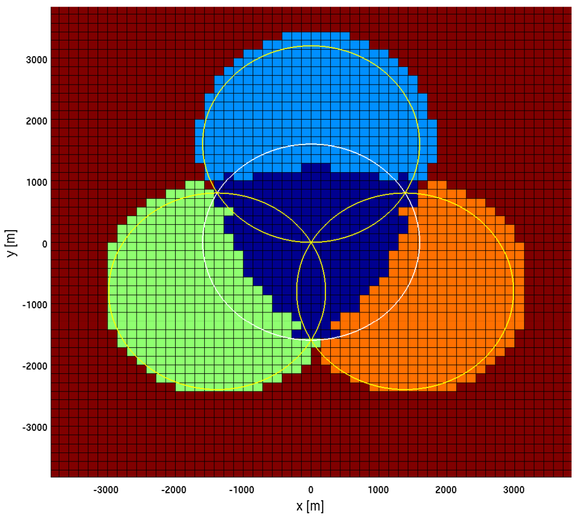
This paper treats the OFDMA and FDD specific properties of 3G-LTE and applies the multihop technology. It emphasizes the resource management perspective on relaying, allowing all multiple access schemes and duplex modes to be seen as similar with respect to the multihop task. For FDD the special properties can be used seamlessly to integrate relaying.



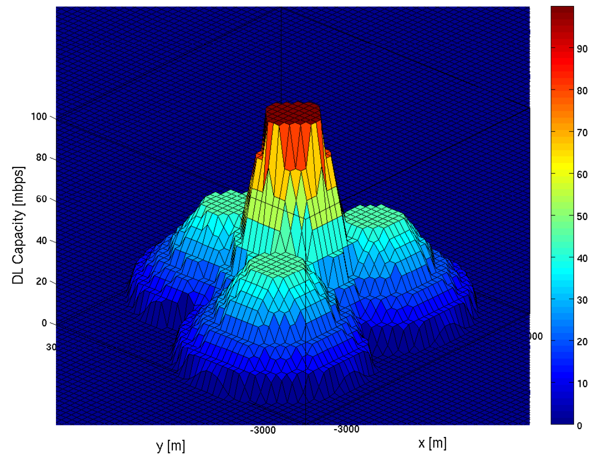
(a) SINR(area)



(b) Rate(area)



(c) Best serving base station (area)



(d) Rate(area)

Fig. 6. Results for the Coverage Extension Scenario

Especially with OFDMA there is a great flexibility to fine-tune resource consumption and interference mitigation. Using an analytic approach, the performance of a multihop scenario to improve the coverage of a radio cell has been studied. We observe that especially in areas suffering from high path loss, at the cell border or around obstructions, relays can be successfully applied.

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