Resource Allocation and Scheduling in FDD Multihop Cellular Systems

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***Abstract*—Cellular radio systems of the next generation aim to make the most out of the available radio resources in the dimensions bandwidth, time and space. The division of time into slots, frames and superframes is standard, both for TDD and FDD duplex modes. OFDMA allows the individual disposition of subchannels as a subdivision of the bandwidth but an aggregation of subcarriers. A basic resource unit is hence a brick in this two-dimensional grid. Space is important both as the location of the base station in whose surrounding the resources are used and in spatial diversity channels. These resources are the scarce good in future radio communications, because they are required proportionally to the traffic demand per area. Due to adaptive modulation and coding schemes and large ranges of possible SINR values, the required resources for a transmission may differ by a factor ten depending on the distances. In this paper we discuss the resource allocation and scheduling mission. We introduce a control system view on the topic, taking adaptive algorithms for modulation, power, subchannel usage and channel quality indication into account.**

***Index Terms*—Resource Allocation Scheduling Half Duplex Control CQI**

I. Introduction

RESOURCES of radio communications are actual abiotic natural resources and they are scarce. Because traffic is time variable the resource demand is time variable. User terminals (UT) are distributed over cells, therefore the demand also varies from cell to cell and in all distance ranges from the base station (BS) from close to the BS to the cell border. Since this spans a wide range of path loss values, there is typically plenty of received power (therefore SINR) at a UT close to a BS, but very few dB only at the cell border. In addition, (multipath) fading is selective in frequency and time, so the received SINR differs for each subchannel (aggregation of OFDM subcarriers) and changes in time. Adaptive Modulation and Coding (AMC) is usually performed by DL resource schedulers to chose a PhyMode (physical layer mode = Modulation and Coding Scheme) which optimally utilizes the available SINR [1] [2].

There is still the question, which subchannel to choose for which UT, independently in downlink (DL) and uplink (UL). This task is strongly related to resource management, which includes resource scheduling (RS) and resource partitioning (RP). RS operates on a frame-by-frame time basis, typically in orders of $1ms$ (see Fig. 1). It decides on the subchannels to use for each UT. This task is called Dynamic Subcarrier Assignment (DSA). It is the typical task that differentiates OFDM from OFDMA, because pure OFDM does not allow multiplexing in frequency while OFDMA utilizes frequency division multiplexing. On a slower timescale there is a resource partitioning algorithm unit that decides which station may use which resource blocks (a larger unit consisting of many resource units). Especially for Multihop cells where relay nodes (RN) are used [3], the resources for the first hop (coordinated by BS) and the second hop (coordinated by RN) must be partitioned so that there is no overlapping and intra-cell interference (with multiple RNs). Resource scheduling requires channel state information (CSI) which is signaled as channel quality indication (CQI) from the UTs to the BS (or RN) [4], [5].

In addition to AMC and DSA [2] another algorithm can be used that regulates the output power of each transmitted subchannel selectively in frequency and time. This Adaptive Power Control (APC) unit tries to compensate in the short-term for the fading notches and in the long term for the distance-caused path loss imbalance between UTs.

This paper discusses resource management using these algorithms and proposes a control theoretic view on the whole task, which includes all the algorithmic blocks mentioned above.

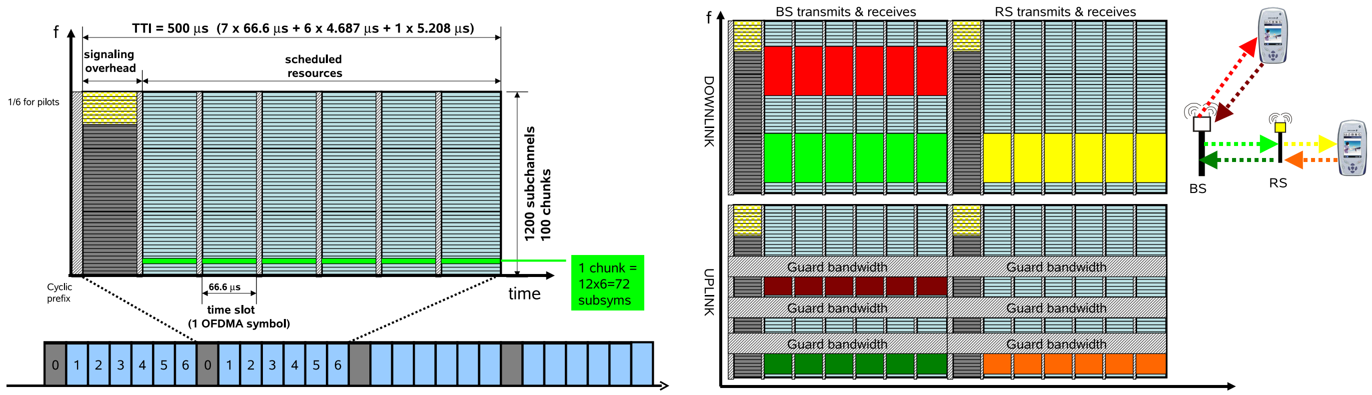
Section II defines Resource Partitioning and Resource Scheduling, Section III presents the closed control loop, and Section IV shows simulation results of the controled scheduler.

II. Resource Management

Resources in Multihop OFDMA systems are typically organized as shown in Fig. 1. In multihop systems the resources for the first and second hop must be separated in time (time division relaying) [7] to avoid co-channel interference and the demand for perfectly sychronized transmitters (Fig. 1(b)). This leads to the resource partitioning problem. How many resources are reserved for the second hop?

In an FDD system two frequency bands are used in parallel. The upper band is used for downlink (DL) transmission from BS to UT and from BS to RN and from RN to UT. The lower band is used for the uplink (UL), i.e. $UT \rightarrow BS$, $UT \rightarrow RN$, $RN \rightarrow BS$. BSs and RNs are assumed to operate in FD mode. UTs may be full-duplex FDD (FDFDD) capable or may only support (half-duplex FDD) HDFDD operation [8]. Figure 2 shows the timing of FDFDD and HDFDD operation in an LTE superframe. Figure 3 shows the timing for half and full duplex UTs in a Multihop environment [9].

Resource Management is the task of organizing these available resources in time, frequency and space. Organization in



(a) One Downlink TTI frame

(b) DL and UL frames for relaying

Fig. 1. Left: TTI Frame format for 3GPP-LTE [6] ($500\mu s$). Right: Resource allocation for two hops.

space means the coordination among BS to avoid the use of the same resources in areas where the coverage of both BSs overlap. This happens severely in all cell edge areas, at the border of a cell, when there is no frequency reuse pattern, i.e. all neighbor cells operate on the same bandwidth ("Reuse-One"). This resource coordination is important for future networks of high spectral efficiency. In this paper only the coordination in time and frequency is discussed, while the neighbor cell activities (neighbor cell resource usage) are treated as uncontrolable interference.

Changes in time happen for the traffic demand of UTs, the mobility of the UTs, and the channel condition. Changes in frequency happen due to the frequency selective fading due to multipath propagation and doppler effects. Therefore a resource scheduler must 1) know the conditions by measurement and reporting (e.g. CQI), 2) know the constraints from the set of partitioned resources and QoS demand of the traffic, 3) decide on which resources to assign to which UT taking the conditions and constraints into account. In the following subsections resource partitioning and scheduling are further defined.

A. Resource Partitioning

Relaying for FDD systems is preferentially organized in the time domain [7], i.e. the radio resources are partitioned among all serving stations (BS and RNs) and the roles alternate in time when a RN is in its serving role. Serving role means ther RN is actively responsible for the resource allocation on the hop towards its UTs. The BS must ensure that the RN is in a task phase where it is acting as a UT ("UT" role) when it is scheduled by the BS to receive the RM or DL data. In Figure 3 the constraints by relaying and half duplex operation are shown. The organisation problem is solved by this super frame timing [9].

To be able to operate RNs, the DL and UL bands are divided between the BS and the RNs during their BS task phase to avoid any intra-cell interference between these stations. This kind of resource partitioning is shown in Figure 4, as an example for the following scenario. It consists of one BS, one RN, three UTs associated to the BS and three remote UTs

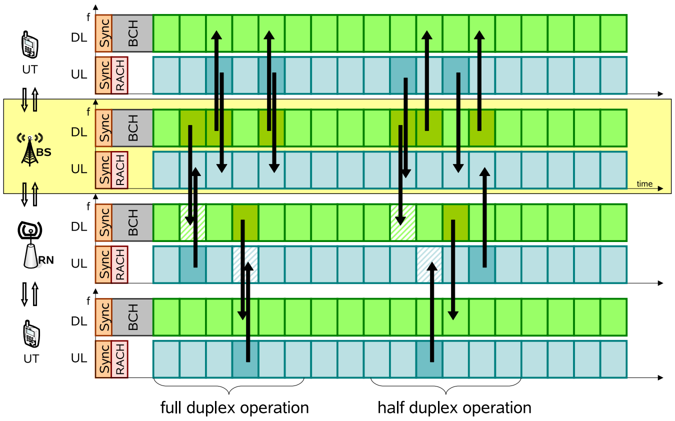


Fig. 2. FDD full and half duplex for 3GPP-LTE [7]

(RUTs) associated to the RN [8]. The only important aspect here is that there is the same traffic demand via the relay RN like from/to the local UTs. Therefore there are three resource request types: 1) The second hop resources for the RUTs, scheduled by the RN but granted as a resource partition by the BS, 2) The first hop resources for the same traffic relayed over RN and 3) The first hop resources for the plain UTs. Assuming the same PhyModes for all links the result of the partitioning is that each resource request types gets one third of the total resources, hence the Figure 4 shows $1/3$ for the resources scheduled by the RN2 and $2/3$ scheduled by the BS1. The even/odd frame imbalance is due to the task phases of the RN. For unequal PhyModes the correct (fair) resource partitioning can be calculated by giving each UT a fair share of the resources [10].

B. Resource Scheduling

Resource scheduling is performed by the BS or RN on the assigned resources given by the resource partitioner. Resource scheduling must not be confused with Packet Scheduling (e.g. for QoS). The latter is not treated in this paper. The decision it taken in every time frame (TTI frame), usually for the next frame but possibly also for more frames in advance. The scheduler takes into account

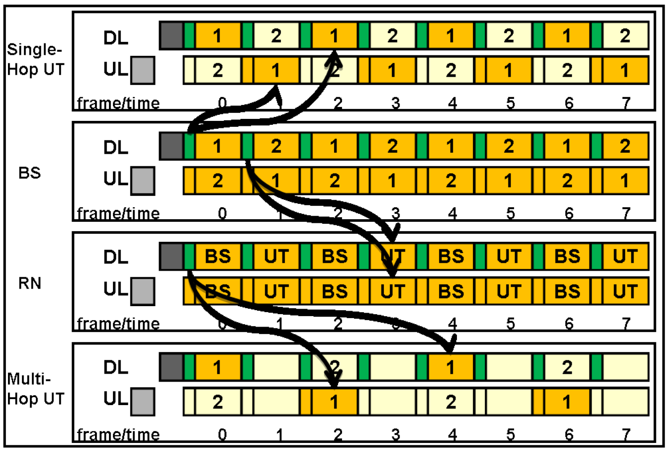


Fig. 3. Superframe for single- and multihop operation with HDFDD UTs and RN TaskPhases [9]; The arrows show to which frame the RM points to; The numbers in the frames give the active duplex group

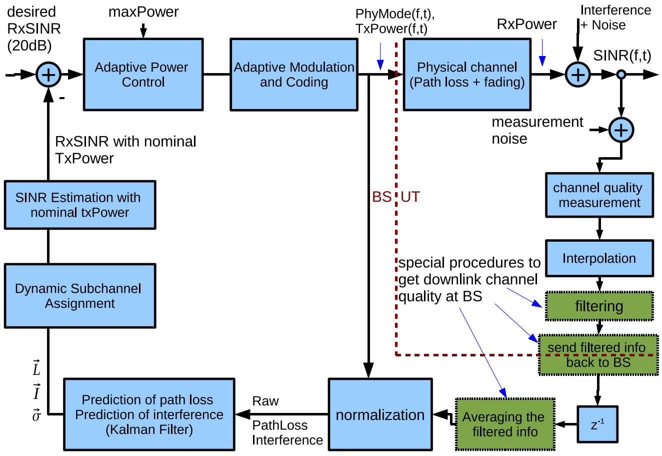


Fig. 5. Closed Loop Control of the OFDMA Subchannel Transmissions

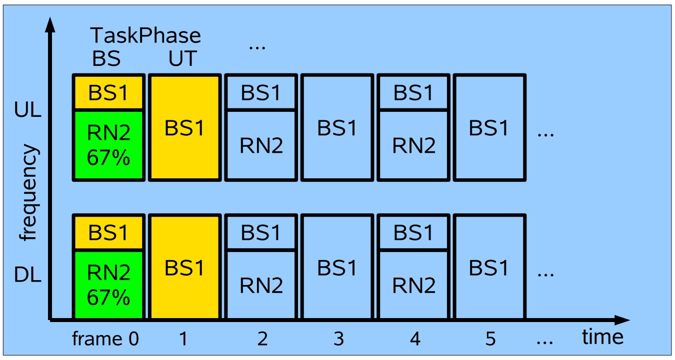


Fig. 4. Resource partitioning between BS and RN [8]

- *resources:* as given by the partitioning,
- *traffic demand:* by the queue occupancies,
- *subchannel capabilities:* by CSI/CQI,
- *QoS demands:* by static priority mapping,
- *Fairness:* by fair strategies within a priority class,
- *subchannel assignment:* by DSA strategies,
- *PhyMode selection:* adaptively by AMC,
- *power allocation:* adaptively by APC,
- *other features:* buffer/overflow management, dynamic segmentation, HARQ retransmission resources, SDMA beamforming and MIMO coordination etc.

So this is a very complex unit and there is no "single one" concept for it at all. A lot of proposals exist for each of these subtasks alone and it is hard to find an optimal solution which fits it all. Fortunately some of these tasks are almost orthogonal and therefore they can be solved step-by-step [1]. In the next section a proposal for this is presented.

III. Closed Loop Control of the Link

Figure 5 shows the closed loop control block diagram of the proposed algorithms for the OFDMA scheduling decisions. As in usual control block diagrams [11], the reference value is on the left and demands the desired SINR at the receiver of $20dB$ as example, because this supports the highest PhyMode, e.g. $QAM64-\frac{1}{2}$. On the right there is the system output, namely the real achieved $SINR$ at the receiver. So obviously the left side of the block diagram is on the transmitter side (BS) while the right one is on the receiver side (UT). The red dotted line is the separation between transmitter and receiver side.

From left to right (between controller and system block) there is a the transmitted power level (per subchannel). The system block contains the path loss and fading, which are obviously time and frequency variable. The outcome is the power level at the receiver of the good signal. Interference and noise power is subtracted to get the $SINR = S/(I+N)$. This is the controlled value, because we want this to be sufficient to support the highest PhyMode without too high packet error probability. The SINR value is measured at the the receiver, usually where pilots are located in the OFDM map. An interpolation block completes the information for all values of time and frequency. The filtering block here reduces this information to a smaller subset, because the signaling information should not waste too much data rate in the uplink. This is a kind of source coding of the CQI information [12]. From sending the symbol, measurement to signaling and back to the sender there is a delay of one round trip time (RTT) which is modeled here by the z^{-1} block. After the CQI information is received at the transmitter side, the source coding is reversed, i.e. the averaging or interpolation block completes the channel state information again to contain values for all points in frequency. A normalization block is necessary, because the received power per subchannel and SINR of course depends on the transmitted power level per subchannel, which is the outcome of the controller. So after normalization we have the actual pathloss $L = P_R/P_T$ as quotient between received and transmitted power. Also the interference power level is a very useful information to be part of the CQI signaling, so that later the correct SINR can be estimated and interference mitigation strategies can be applied. After normalization a prediction for the future is necessary, because there was already a measurement delay of one RTT and the scheduling decision is for even one more frame into the future. The result of this block is a path loss vector $\vec{L}$, an interference power vector $\vec{I}$ and a vector that quantifies the prediction or estimation error $\vec{\sigma}$. These are the input values of the scheduler decision blocks.

Given these values the DSA problem can be solved. Not shown here is that the traffic demand limits the number of subchannels needed. The algorithm prefers the subchannels with the smallest path loss. But there is a freedom of choice how to cope with multiple UTs if they are in competition (traffic overload, full queues). Shown here is only one control loop for one UT, but in reality there are multiple loops, one for each UT. And they are coupled at the DSA block until the APC block.

After having decided on the used resources for each UT and each subchannel i, the $SINR$ estimation is straightforward. Interesting is that we must assume to use the nominal transmit power $P_T = P_{T,nominal}$ because the actual power level is not known yet.

$$SINR_{nominal,i} = \frac{P_{T,nominal} \cdot L_i}{I_i + N} \quad (1)$$

The controller can then compare the nominal $SINR$ with the desired $SINR$ and depending on sign and amount of the difference, the adaptive power control block can increase or decrease the actual transmit power $P_{T,i}$ to achieve the desired $SINR$ level. There is of cource a limiter function inside, because the power per subchannel can only be adapted within certain bounds. Especially to the limit is reached $P_{max,i}$ frequently for UTs at the cell border. There is also a global maximum power $P_{max,total}$ which is given by the RF amplifier and EIRP limit regulations.

At this point the estimated SINR is known on each subchannel and the adaptive modulation and coding block will decide on the PhyMode given the link level results.

The Packet Scheduling task was not treated here, but it can be modelled by linking it to the DSA block, because the best subchannels are chosen for certain UTs and flows [13] within. The shown diagram in this form is valis for the DL scheduling. For the master UL scheduling (in the BS), there need to be resource requests instead of queues, and the CQI blocks become simpler.

This model helps to understand the interaction between all the involved algorithms and provides a promising tool for further analysis.

IV. Simulation Results

Simulations have been carried out using the OpenWNS system simulator [14] in a cellular environment with one BS and one UT, for simplicity. Table I shows the main parameters. The channel is fast fading with $10Hz$ doppler shift and almost no correlation between subchannels (worst case). There are two systems in comparison. One system (A) which assumes a flat channel and does no power control and therefore uses the same PhyMode on all resources and the second system (B) which has all channel knowledge, and uses appropriate DSA, AMC, APC algorithms.

Figure 6 shows the used PhyModes on all the subcarriers and time slots chosen by AMC. The histogram in Figure 7 shows this in another way, where the AMC block choses PhyModes with different frequency. Figure 10 shows the special case of one PhyMode ($QAM64 - \frac{2}{3}$ supporting $MI = 4$).

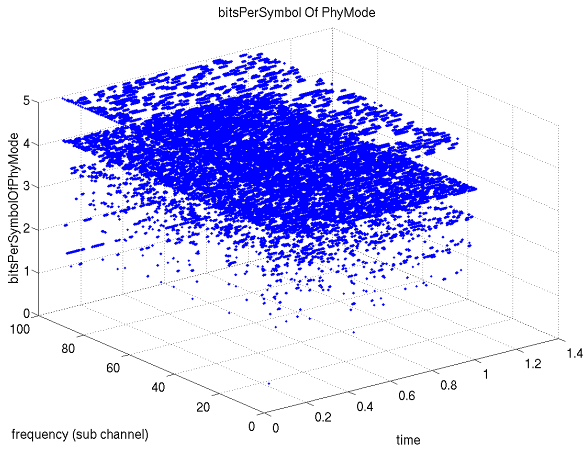


Fig. 6. Used PhyModes with AMC for the resource units in frequency and time. $BitsPerSymbol$ means the mutual information that can be achieved with the PhyMode

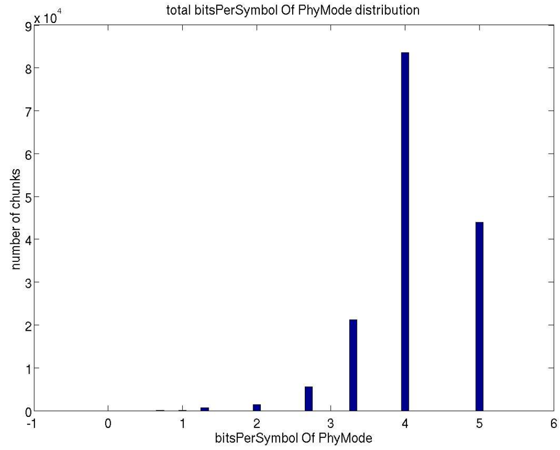


Fig. 7. Probability density functions of the used PhyModes with AMC

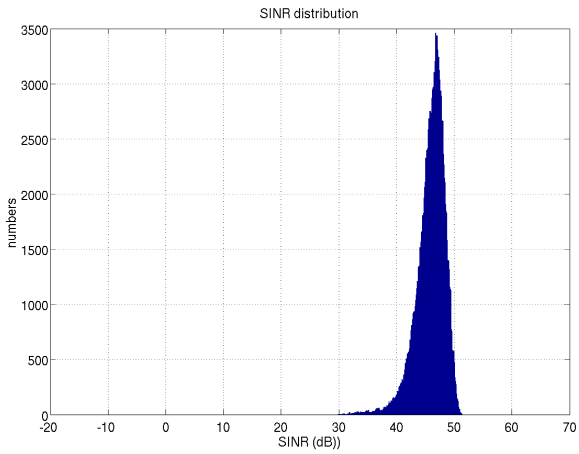
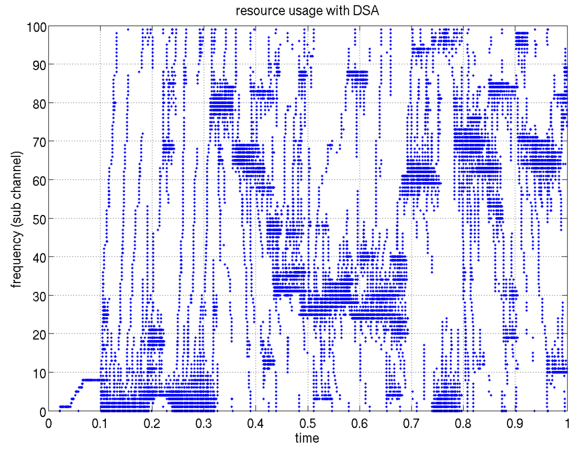


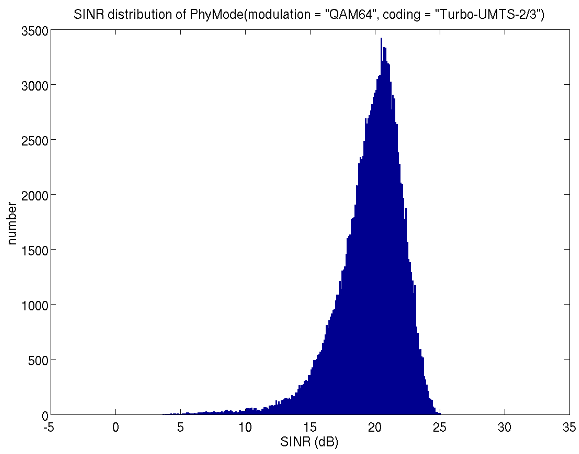
Fig. 8. Without Adaptive Power Control (APC) the SINR at the receiver is distributed like this and much too high for UTs close to the BS

(a) Scheduler without DSA

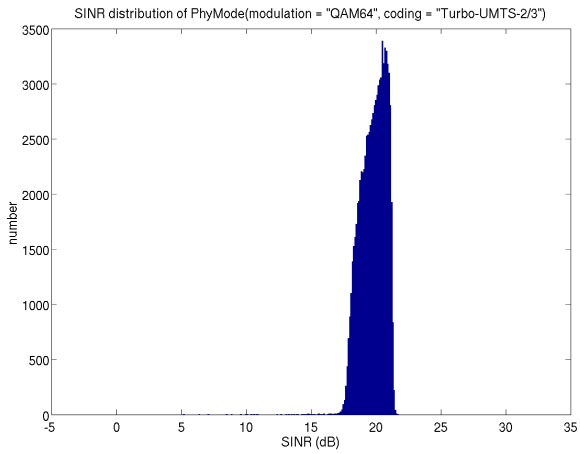


(b) Scheduler using DSA

Fig. 9. Used DL resources in time and frequency with and without Dynamic Subcarrier Assignment (DSA)



(a) Scheduler without AMC. Here only one PhyMode is used



(b) Scheduler using AMC. Here only the $SINR$ of one PhyMode is shown

Fig. 10. probability density functions of the SINR at the receiver with and without Adaptive Modulation and Coding

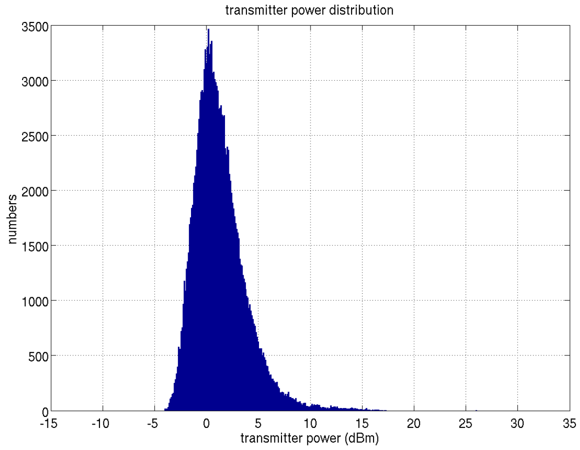
If this is chosen on all subchannels, because the CSI is not known, the histogram in Figure 10(a) shows that the received $SINR$ is too broadly distributed. In many cases it is below the $SINR_{min}$ for this PhyMode. With AMC this PhyMode is only chosen where the SINR is suitable, as shown in Figure 10(b), while other PhyModes are chosen outside of this $SINR$ interval.

The subcarrier choice in DSA for a small traffic load of 10% is shown in Figure 9. Without selective DSA simply the smallest subchannel numbers are chosen. With DSA prefering the best subchannels, this uses the potential of the whole bandwidth and avoids the fading gaps.

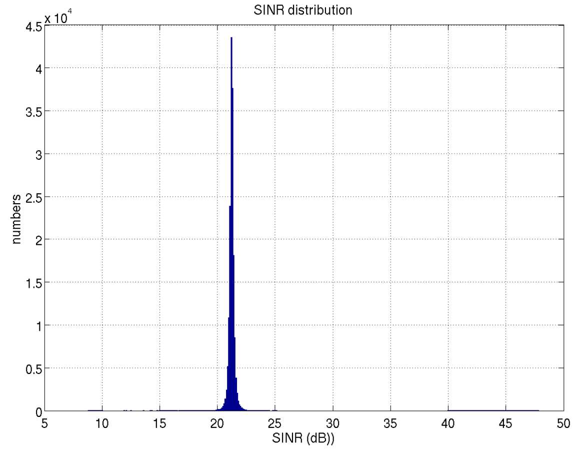
APC has been simulated with a UT closer to the BS, because APC helps reducing the transmit power and therefore reduces the interference into the neighbor cells. Figure 8 shows the typical $SINR$ value at a UT close to the BS when constant transmit power around $30dBm$ was used and Rayleigh fading dominates the path loss. The same situation with APC reveals that the control goal of $SINR = 20dB$ (plus a safety margin of $2dB$) can be achieved. In Figure 11(b) a sharp peak at $22dB$ can be seen. Interesting is that the transmit power output of the controller (shown in Figure 11(a)) is now

Parameter	Value
radio frame length	$10ms$
TTI frame length	$500\mu s$
frames per superframe	20
OFDM symbol duration	$66.7\mu s(+CP)$
carrier frequency	$2.10GHz$ DL, $1.92GHz$ UL
channel bandwidth	$2x20MHz$
number of subcarriers	1200 (DL&UL)
number of subchannels	100 (DL&UL)
PhyModes: Moduilation	QPSK, 16QAM, 64QAM
PhyModes: Coding	Turbo$\frac{1}{3}$ to $\frac{5}{6}$
Transmit power P_T	$46dBm$ (BS) total
Nominal power $P_{nom,i}$	$26dBm$ (BS) per subchannel
Cell size	1600m
Cluster order (f reuse)	7

TABLE I
GENERAL SIMULATION PARAMETERS



(a) Transmit power distribution (controller output)



(b) SINR distribution at the receiver

Fig. 11. Using Adaptive Power Control (APC) in DL: Transmitted and received power probability density functions

distributed symmetrically to the pathloss distribution pdf. The study assumed continuous control of the power value P_T. In reality, however, there are quantization steps due to DACs and limitations (upper and lower bounds). Obviously a lot of power can be saved that does not appear as interference into neighbor cells. Other preliminary simulation results showed that artificially reducing the received SINR leads to slightly higher packet error rates and reduced throughput. Future studies can compare this aspect against the gains due to reduced neighbor interference.

V. Conclusion

In this paper the manifold aspects of packet and radio resource management and scheduling in OFDMA based multi-hop cellular mobile radio systems are presented. One special focus hereby is the integration of decode-and-forward layer 2 relays for coverage extension and capacity enhancement. Furthermore a new closed loop control model of the wireless link is introduced which includes all the typical tasks of the resource scheduling like Dynamic Subcarrier Assignment, Adaptive Modulation and Coding, Adaptive Power Control, Channel Quality Indication and shows their dependencies, in order to cope with the inherent time and frequency diversity of OFDMA systems. With this model the complexity of the system can better be understood and analyzed. By a combination of radio resource partitioning between BSs and their RNs and packet scheduling strategies the fair support of single- and multi-hop as well as full- and half-duplex FDD terminals is assured. Finally simulation results show the necessity of the introduced RRM concepts and the benefit of using a closed loop control approach. In the future relay-enhanced multi-cellular scenarios shall be further investigated by means of simulations, in order to show the benefits of the introduced concepts in terms of improved spectral efficiency. There will also be more analysis of the influence of the potentially many different block strategies involved.

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