Adaptive Power Control for 4G OFDMA systems on Frequency Selective Fading Channels

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***Abstract*—Future cellular radio systems aim at maximizing the spectral efficiency. OFDMA radio resources are the scarce good with their dimensions bandwidth, time and space. Due to frequency selective fading the effective pathloss varies in all dimensions. Adaptive algorithms are available which allocate the best modulation and coding scheme depending on the expected SINR, as well as dynamic subchannel assignment which aims to choose the best subchannel for each user. This already boosts the performance of OFDMA system. However, these algorithms alone do not touch the transmitted power per subchannel. On the cell edge this is fine, but large areas are covered with a transmitted power exceeding the usually required SINR. In this paper we introduce a power control which saves power on the users within the cell. This leads to a reduced interference into neighbor cells, especially for future reuse one systems. Also some of the saved power can be used to boost transmissions at the cell edge. In this paper we introduce an adaptive power control concept and arrange it into a closed loop control system which contains blocks for all adaptive algorithms for modulation, power, subchannel usage and channel quality indication.**

***Index Terms*—Scheduling, Adaptive Power Control, CQI, FairSINR**

I. Introduction

RADIO transmission power determines the coverage area of a radio cell. User terminals (UT) are assumed to be distributed evenly in a cell (constant user density), therefore UTs appear in all distance ranges from the base station (BS) from close to the BS to the cell border. This means a wide range of path loss values will appear. At a UT close to a BS (cell center users), there is typically plenty of received power P_R ($\rightarrow SINR$) At the cell border, the $SINR$ drops down to $0dB$. Additionaly, fading is selective in frequency and time, so the received $SINR$ also varies in these dimensions. Each subchannel (aggregation of OFDM subcarriers) is affected by this.

For OFDMA, the decision on which subchannel to choose for which UT is taken by the Dynamic Subcarrier Assignment (DSA) task of a radio resource scheduler. It typically selects the best subchannel for each UT according to some metrics [1]. Resource scheduling like this requires channel state information (CSI). CSI is signaled as channel quality indication (CQI) from the UTs to the BS (or RN) [2], [3].

The variations of $SINR$ within one subchannel are treated adaptively with Adaptive Modulation and Coding (AMC). It is usually performed by resource schedulers to chose a PhyMode (physical layer mode = Modulation and Coding Scheme) which optimally utilizes the available SINR [4] [5]

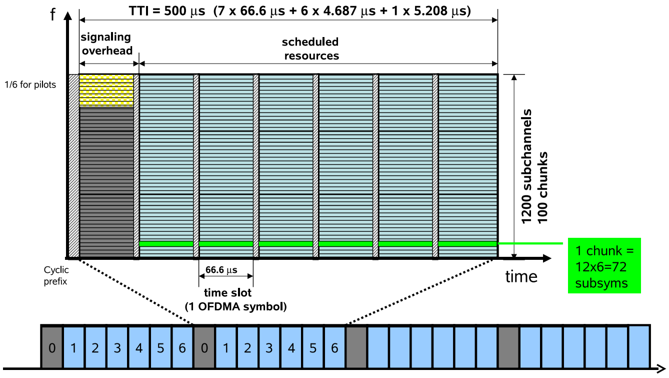


Fig. 1. One Downlink TTI frame for LTE

and approximate the Shannon bound (see Fig. 3). But there is also an inner region of the cell where the $SINR$ is $> 20dB$ and the highest PhyMode is always chosen. For these locations the transmit power is higher than necessary, which also means the interference into neighbor cells is much higher than required. Especially for future reuse one systems, the interference is an important task.

Therefore, in addition to AMC and DSA [5], it is possible to regulate the output power on each transmitted subchannel selectively in frequency and time. This topic is rather new in the literature [6]. 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. In this paper it is assumed that the control is continuous and piecewise linear, with only an upper limit of the power per subchannel, but no (DAC) quantization and no lower limit.

This paper discusses the control aspects of APC using a control theoretic view on the radio link. The APC strategy “FairSINR” is introduced which aims to provide each UT with the same SINR at the receiver. It is shown that this strategy and closed loop power control essentially mean the same.

Section II defines the required aspects of Resource Scheduling, Section III focuses on the Adaptive Power Control aspect and Section IV integrates this as a building block into the control model. Section V presents simulation results of the APC performance.

II. Adaptive Resource Scheduling Task Functions

Before defining the task functions that adapt the OFDMA transmission to the fading channel conditions we need a model of the resources (the service that the scheduler offers) and the demand (service consumers). The latter is just traffic measured by number of PDUs currently in the queues.

OFDMA resources are organized like shown in Fig. 1 in the Multihop case. The resources for the first and second hop must be separated in time [7] to avoid co-channel interference. A resource partitioning unit is responsible to assign resources for the first and second hop [8].

An organization of resources in space means the coordination among BS to avoid the use of the same resources in areas where the coverage of both BSs overlap. This is required in "Frequerncy Reuse One" multicellular systems, when all neighbor cells operate on the same bandwidth. This kind of resource coordination is assumed for future networks of high spectral efficiency. In this paper only the single cell coordination in time and frequency is assumed, while the neighbor cell activities (neighbor cell resource usage) are treated as uncontrolable interference.

A. Channel Quality Indication

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 know the channel conditions by measurement and reporting (CQI), know the constraints from the set of partitioned resources and QoS demand of the traffic, and decide on which resources to assign to which UT. In Figure 4 there are all the necessary steps [3] shown including filtering, normalization and prediction.

B. Resource Scheduling Tasks

Resource scheduling (RS) 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 resource scheduler performs these steps:

- *OFDMA resources:* as given by the partitioning,
- *subchannel capabilities:* by CSI/CQI [3],
- *subchannel assignment:* by DSA strategies,
- *PhyMode selection:* adaptively by AMC [9],
- *power allocation:* adaptively by APC,
- *other features:* dynamic segmentation, HARQ retransmission resources, SDMA beamforming and MIMO coordination etc.

A lot of proposals exist for each of these subtasks alone and it is hard to find an optimal solution which fits it all [10]. Fortunately some of these tasks are almost orthogonal and therefore they can be solved step-by-step [4], [11]. In the next sections the blocks are expained more in detail.

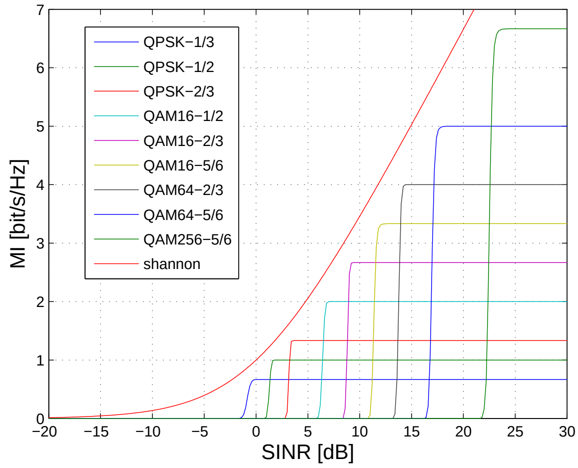


Fig. 2. Link level results for different modulation&coding schemes (PhyMode) for LTE [9]. $QAM256$ is extrapolated and not part of the LTE standard.

C. DSA Strategies

The dynamic subchannel assignment (DSA) task is performed in each time frame and decides the assignment $A_{u,c}$ for the user u to the subchannel c. Here we assume full buffers for simplicity.

$$A_{u,c} = \begin{cases} 1, \text{if u is mapped to c} \\ 0, \text{if u is not mapped to c} \end{cases} \tag{1}$$

Let the subchannel c be one out of $0..(C-1)$, and user UT be u out of $0..(U-1)$. Then the contraints are: There must be at most one $A_{u,c} = 1$ for a specific c and all u:

$$\sum_{u=0}^{U-1} A_{u,c} \leq 1 \tag{2}$$

A traditional DSA algorithm tries to maximize the capacity ϵ subject to the constraints above, where $MI_{u,c}$ means the mutual information achievable for user u and subchannel c.

$$\epsilon = \sum_{c=0}^{C-1} \sum_{u=0}^{U-1} MI_{u,c} \cdot A_{u,c} \tag{3}$$

This is solved by (integer) linear optimization or smart heuristics and is known to be optimal regarding throughput, but totally not fair among UTs. A completely different optimization goal is the fairness of users, which can be achieved by maximizing the MaxMin fairness criterion, i.e. maximizing ϕ, the minimum rate of all users u:

$$\phi = min_u(\sum_{c=0}^{C-1} MI_{u,c} \cdot A_{u,c}) \tag{4}$$

This is called MaxMin Capacity Optimization [1].

Many more DSA strategies exist [5], but these are the most prominent.

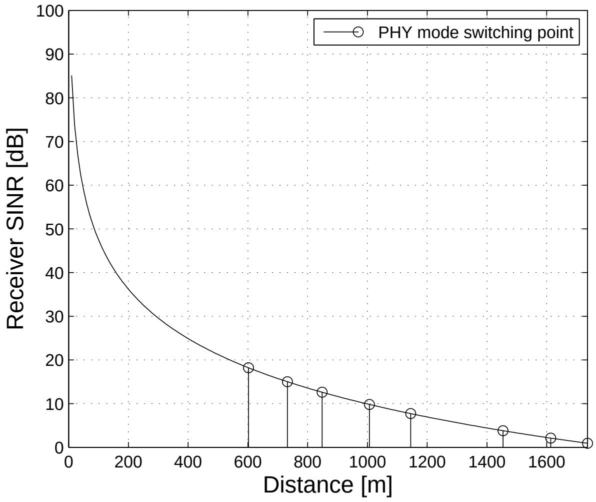


Fig. 3. SINR as a function of distance d due to pathloss using nominal transmit power (no APC) in an LTE NLOS scenario. Switching points according to Fig. 2. Analytic results.

D. Adaptive Modulation and Coding

Each resource chunk on a subchannel c can carry a number of bits proportional to the mutual information $MI_{u,c}$ [12] which depends on the $SINR_{u,c}$ and $PhyMode_{u,c}$. These link level results determine the Adaptive Modulation and Coding (AMC) [9], because the $PhyMode_{u,c}$ is chosen based on the estimated $SINR_{u,c}$ (see Fig. 2).

III. Adaptive Power Control

The Adaptive Power Control (APC) unit regulates the output power of each transmitted subchannel selectively in frequency and time. The motivation for using APC is to adapt to the channel conditions (fading) and to equalize the path loss imbalance between UTs of different distances to the BS.

We assume for simplicity that the power P_c per subchannel c can be adjusted continuously (without quantization steps), unbounded towards the lower limit $0mW$ but bounded towards the upper limit $P_{max,subchannel}$. There is also a global maximum power $P_{max,total}$ which is given by the RF amplifier and EIRP limit regulations. So we have these constraints:

$$\forall c : P_c \leq P_{max,subchannel} \tag{5}$$

$$\sum_{c=0}^{C-1} P_c \leq P_{max,total} \tag{6}$$

For APC there are degrees of freedom within the constraints given by eq. 5 and 6. So it is natural that not only one but multiple possible solutions exist. This allows to define APC strategies with different objectives. Let's assume DL APC only, since the UL power control is similar, except that the BS controls the power, commands it to the UT which only installs this power level but does no decision on its own.

The simplest APC strategy is *nominalPower* which just assigns $P_c = P_{nominal,subchannel}$. This is as trivial as having no APC at all. The result is that the received power $P_{Rx,u}$ in a UT u at distance d_u behaves according to the pathloss statistics $P_{Rx,u} = P_{Tx,u}/L_u$. The pathloss L is typically like

$$\frac{L_{u,c}}{dB} = 10\gamma log\frac{d_u}{km} + \frac{L_{fading,u,c}}{dB} + const. \tag{7}$$

with a $\gamma \approx 4$ for non-line-of-sight (NLOS) links or $\gamma \approx 2.2$ for LOS links. So the signal-to-interference-plus-noise ratio $SINR_u = P_{Rx,u}/(I_u + N)$ also behaves like this (in the dB domain). $L_{fading,u,c}$ accounts for the time and frequency dependent fading.

In consequence, in a huge distance range close to the BS the $SINR$ is higher than $20dB$ (the comfortably required value to support the highest PhyMode, see Fig. 2). Then there is a distance range of $0..20dB$ (the outer cell belt) where all PhyModes occur, and the cell edge and beyond range with $SINR < 0dB$. When relays are used, this fraction of the cell area is even lower [9]. The observation in Fig. 3 is that some transmitted power is wasted on those subchannels that are assigned to the UTs close to the BS. This excess power appears as interference into neighbor cells (should always be avoided). Also, analytically eq. 6 allows that power saved on some subchannels can be used on other subchannels as long as the total power and $P_{max,subchannel}$ is not exceeded.

Instead we propose an APC strategy "FairSINR", which aims at equalizing the received $SINR_u$ for all UTs. Imagine a straight constant flat value in Fig. 3 instead of the exponential decay. This theoretically implies the regulation of the TxPower $P_{Tx,u,c}$ of a user u on subchannel c as

$$\frac{P'_{Tx,u,c}}{dBm} = \frac{L_{u,c}}{dB} + \frac{I_{u,c} + N}{dBm} + \frac{SINR_u}{dB} \tag{8}$$

and in reality considering the subchannel power constraints:

$$\frac{P_{Tx,u,c}}{dBm} = \frac{\alpha}{dB} + \frac{min(P'_{Tx,u,c}, P_{max,subchannel})}{dBm} \tag{9}$$

The correction factor α should be $0dB$. But if there is total power left over it can be $\alpha > 0dB$; or if it the total power is exceeded it must be $\alpha < 0dB$. The constraint in eq. 6 defines the possible range for $\alpha \in [-\infty; \alpha_{max}]$.

$$\alpha_{max} = P_{max,total} \div \sum_{c=0}^{C-1} P_c \tag{10}$$

If $\alpha > 0dB$ is feasible according to eq. 10, this allows to exceed the $SINR_{desired}$ value. The advantage is to reduce the probablity to fall below a the switching point (Fig. 2 and 3) for the case that the CQI measurement is inaccurate (due to fast fading, high terminal velocity). The disadvantage is the increased interference into the neighbor cell ($I_{u,c}$ in the neighbor cells), which is hard to estimate and predict when performing a fully dynamic subchannel assignment. An $\alpha < 0dB$ means there is a total power limitation and each supplicants' $SINR_u$ must be reduced below $SINR_{desired}$. In turn, the PhyMode also needs to be adapted (reduced) for each UT. The equal treatment implies the name "FairSINR". Other strategies are currently under inverstigation.

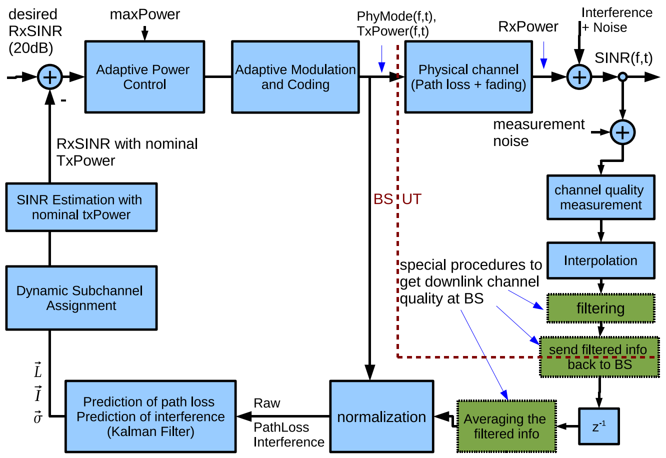


Fig. 4. Closed Loop Control view of the OFDMA DL resource scheduling tasks. The desired $SINR$ at the receiver is sufficient to support the highest possible LTE PhyMode (Fig. 2).

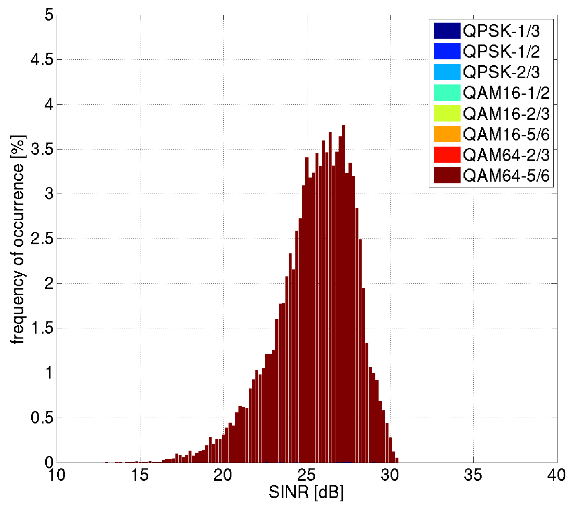


Fig. 5. SINR at the receiver without Adaptive Power Control (APC) at a distance = $768m$)

IV. Closed Loop Control

The closed loop control block diagram in Figure 4 defines an order of execution. Control block diagrams [13] take the reference value ($SINR_{desired}$) on the left, and compare it with the estimated $RxSINR$ assuming that the nominal $TxPower$ is used for this subchannel. According to Fig. 2, $20dB$ are requested to supports the highest LTE PhyMode $QAM64-\frac{1}{2}$. $Rx\vec{SINR}$ and most other values are vectors over all subchannels, because every subchannel can be treated independently with adaptive OFDMA. On the right there is the system output, which is the real achieved $SI\vec{N}R$ at the receiver. The system blocks are distributed over several stations. The left side of the block diagram is on the transmitter side (BS) while the right side is on the receiver side and represents one out of all UTs. In a real radio cell there are multiple UTs which all receive the OFDM symbol and send CQI feedback back to the BS. Shown here is only one control loop for one UT, but in practice there are multiple loops, one for each UT. They are coupled through the blocks DSA until APC.

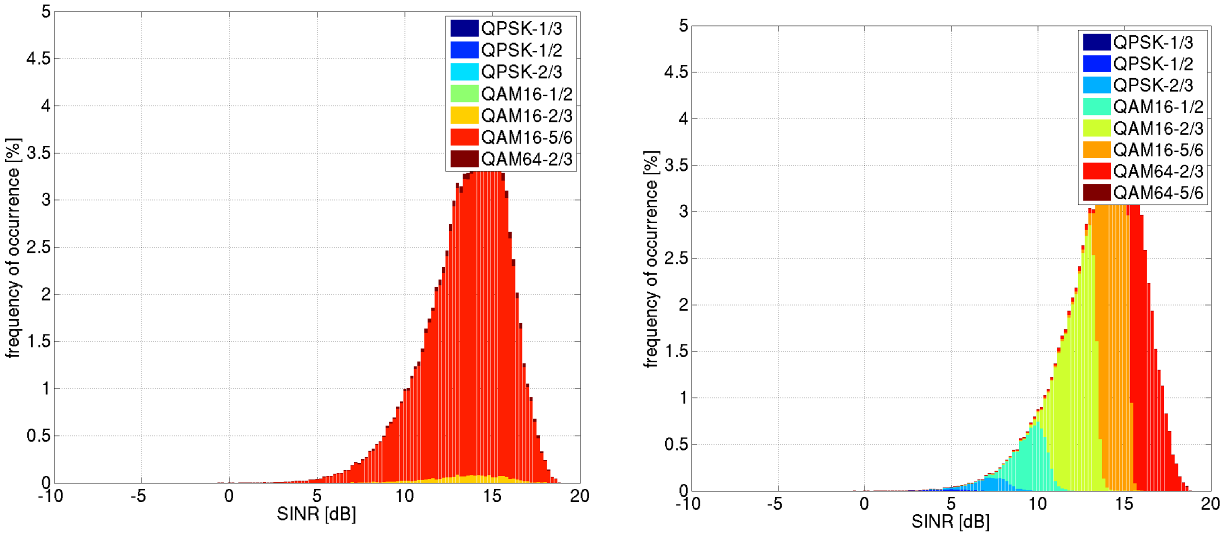
The red dotted line is the separation between transmitter and receiver side. Exactly at the junction on the upper (forward) path (between controller and system block) the transmitted power level is available (a vector over all subchannels). The system block right of this contains the path loss and fading, which are obviously time and frequency variable. The output is the power level $\vec{P_R} = Rx\vec{Power}$ at the receiver. Interference and noise power is subtracted here to get the $SI\vec{N}R = Rx\vec{Power}/(I+N)$. This is the controlled value (see above), because we want this value to be sufficient to support the highest PhyMode ($\geq 18dB$) without too high packet error (PER) probability (see Fig. 2). The SINR value is measured at the the receiver by analyzing pilot signals that are located all over the OFDM map. An interpolation block completes the information for all values of time and frequency. The following filtering block reduces this information to a smaller subset, because the signaling information should not waste too much data rate in the uplink [14]. This is a kind of source coding of the CQI information.

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 BS side, the source coding is reversed, i.e. the averaging (interpolation) block completes the channel state information again to contain values for all points in frequency. A normalization block is necessary here, because the received power per subchannel $Rx\vec{Power}$ and $SI\vec{N}R$ of course depend on the transmitted power level per subchannel $\vec{P_T} = Tx\vec{Power}$, 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. Normalization is possible, because in the BS we know the power levels we used in the past for each subchannel.

Also the interference power level $\vec{I}$ is a very useful information and should be part of the CQI signaling [3], 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 usually done for even one more frame into the future [15]. 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 DSA and following blocks. With these values the DSA problem can be solved (section II-C).

The DSA algorithm "best channel" prefers the subchannels of one UT 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). This is the task of a packet scheduling strategy (not shown here for simplicity).A packet scheduling strategy "max throughput" prefers UTs with the smallest path loss (cell center users), because this maximizes the total capacity, while strategies like "proportional fair" aim at equalizing the data rate for each UT (in case of overload).

After having decided on the used resources for each UT and each subchannel i, the $SINR$ estimation is straightforward.



(a) Scheduler without CQI information (flat channel assumption). AMC decides one PhyMode only

(b) Scheduler using full CQI and AMC. Here the conditional distributions per PhyMode are shown

Fig. 6. probability density functions of the SINR at the receiver with and without CQI channel estimation data. Distance = $1600m$. Note the valid intervals for PhyModes of Fig. 2. Simulation Results.

Interestingly we must assume to use the nominal transmit power $P_T = P_{T,nominal}$ here because the actual power level is not known yet (not until the AMC block):

$$SINR_{nominal,i} = \frac{P_{T,nominal} \cdot L_i}{I_i + N} \quad (11)$$

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 (APC) block can increase or decrease the actual transmit power $P_{T,i}$ to achieve the desired $SINR$ level as shown in section III.

At this point the estimated $\vec{SINR}$ is known on each subchannel and the AMC block will decide on the PhyMode given the link level results.

Figure 4 is valid for DL scheduling, but the UL is analogous. For the master UL scheduling (in the BS), there are resource requests instead of queues. The CQI functions are much simpler, because the UL is measured and scheduled both in the BS. DSA, APC and AMC take their decisions also for the UL and communicate them with resource usage maps that are signaled to the UTs.

V. Simulation Results

The controlled system with all adaptive algorithms has been studied using the OpenWNS system simulator [16]. The scenario was a cellular environment with one BS and one UT, for simplicity. The channel is fast fading with $10Hz$ doppler shift and almost no correlation between subchannels (worst case). There are two systems in comparison. System A (Fig. 6(a)) assumes a flat channel and does not perform power control and therefore uses the same PhyMode on all resources and system B has all channel knowledge due to CQI and can use all appropriate DSA, AMC, APC algorithms. This is evaluated for two typical distance ranges ($d = 1600m$ and $d = 768m$).

The first scenario emphasizes cell edge users ($d = 1600m$). Without correct CQI, Figure 6(a) shows that AMC selects one PhyMode ($QAM16 - \frac{5}{6}$), but many $SINR$ values are beyond the allowed bounds according to Fig. 2; in many cases it is below the $SINR_{min}$ for this PhyMode. With CQI and AMC but without APC, the correct PhyModes are chosen for each SINR, as shown in Figure 6(b).

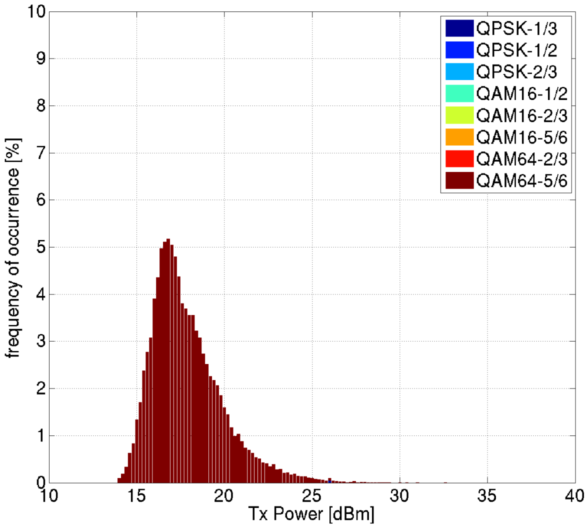
At a shorter BS-UT distance ($d = 768m$) the $SINR$ is much more than sufficient (Figure 5). A constant transmit power of $26dBm$ was used and rayleigh fading dominates the path loss. This is where APC is beneficial. With APC switched on, it reduces the transmit power significantly (Fig. 7(a)) and therefore reduces the interference into the neighbor cells. The APC result in Figure 7(b) reveals that the control goal of $SINR = 18dB$ can be achieved. A sharp peak can be seen here. Interesting is that the transmit power output of the controller (shown in Figure 7(a)) is now distributed symmetrically to the pathloss distribution pdf. Around $10dBm$ can be saved here. These $10dBm$ now do not interference into neighbor cells. Even higher gains are possible for UTs closer to the BS ($d < 768m$).

It is interesting to note that using APC makes AMC less necessary, because there is only one target PhyMode and power is controlled to achieve its optimum SINR.

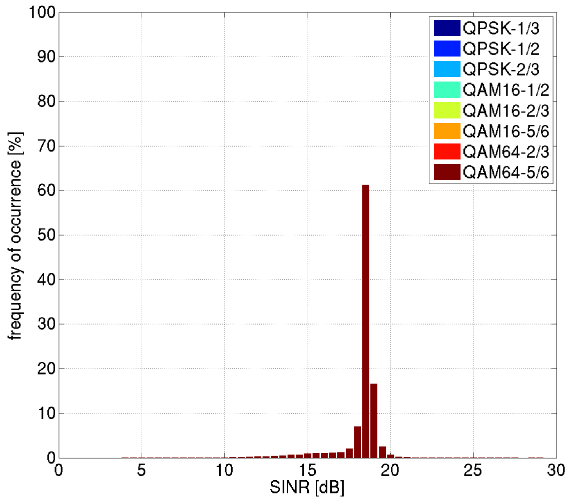
Both APC and AMC rely on correct CQI. If the fading is faster, both are expected to perform worse. For this case a higher SINR margin is recommended. Alternatively for ultra fast fading, a simple DSA strategy could just evenly distribute the subchannels to utilize transmit diversity [5].

VI. Conclusion

This paper treated the adaptive power control aspect inside layer two in a mobile radio system. This is one of the OFDMA resource scheduling tasks, next to DSA. A closed loop control model is then introduced which contains APC



(a) Actual transmit power distribution using APC (controller output). The nominal power would be $26dBm$ per subchannel.



(b) SINR distribution at the receiver when APC is applied. Compare with Fig. 5.

Fig. 7. Using Adaptive Power Control (APC) in DL: Transmitted and received power probability density functions. Distance = $768m$.

and all other adaptive tasks as building blocks. This model allows to handle the complexity of the system better and to study their dependency. The power control by APC is implicitly incorporated in this closed loop approach. Simulation results show a significant power reduction using APC. Future research will investigate more APC strategies together with DSA strategies and analyze the spectral efficiency in a multi-cellular scenario. Another important future aspect is the QoS prioritization on a flow basis [17], which can be extended to prioritize transmit power reserves.

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