4G Cross-Layer Closed Loop Control Scheduling

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***Abstract*—Packet and Resource Scheduling are two distinct tasks inside the medium access control layer of a wireless system of the fourth generation. Packet scheduling is the determination of the ordering of packets among competing connections or users, where the server itself is not specified. Resource scheduling (RS) is the determination of the resources of the wireless link to use for which user, while the meaning of the packets is not important. We claim that these tasks should be separated as much as possible so that the problems can be solved in smaller units. In this paper we propose a block diagram for the various tasks of resource scheduling, while the separated packet scheduling is done as known from QoS support in wired networks.**

I. Introduction

PACKET and Resource Scheduling are two distinct tasks inside the medium access control layer of a wireless system of the fourth generation. Packet scheduling determines the order of packets, choosing among competing connections or users in order to achieve QoS. Resource scheduling prepares the resources of the wireless link to be used by the packets. These tasks can be separated largely so that the solution can be found much simpler. A block diagram for the tasks of resource scheduling is presented, and packet scheduling is integrated into the model as well.

The algorithms control the physical layer settings, such as the Modulation and Coding Scheme (MCS), also called PhyMode, but also transmit power levels and subchannel mappings. Towards higher layers the packet scheduler interacts with traffic sources and sinks by taking their QoS requirements into account. Therefore this is a true coordination across layers.

In cellular systems of the future IMT Advanced family (4G) the base station controls resources centrally while relays can take over a part of the responsibility on the second hop. The OFDM channel is frequency selective and time variant so there is a need for adaptive algorithms to utilize the channel optimally. Channel state dependent resource scheduling relies on accurate channel quality indication so there is always a loop from base station to user terminal and back. Legacy algorithms simply use their input knowledge and decide upon that.

There are also orders of magnitude for the pathloss due to huge distance ranges between base stations (BS) and user terminals (UT). Relays have been shown to help in the coverage and capacity issues of such radio cells [1]. Since the pathloss values span such a huge interval, 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 the operating region for signal-to-interference+noise ratios $SINR$ of zero to $20dB$ OFDM systems typically adapt the PhyMode. Adaptive Modulation and Coding (AMC) is the unit that performs this task in the DL resource schedulers. This utilizes the available SINR close to the cell border very well [2], [3] and reaches spectral efficiencies close to the shannon bound (for single-antenna systems, SISO). For MIMO, there are virtually more spatial channels, and AMC is performed on each of them [4].

Another important task of resource scheduling is the decision, which subchannel to choose for which UT, independently in downlink (DL) and uplink (UL). This task is called Dynamic Subcarrier Assignment (DSA) [3]. For multihop systems, this task requires resource partitioning (RP) before [5]. DSA requires channel state information (CSI) which is signaled as channel quality indication (CQI) from the UTs to the BS (or RN) [6].

An Adaptive Power Control (APC) unit regulates the output power of each transmitted subchannel selectively in frequency and time [7]. It compensates for the fading notches in the short-term and for the distance-caused path loss imbalance between UTs in the long term. There is a limitation by the total maximum power, but in many cases close to the BS power can even be saved.

In this paper the interaction, order and performance in a control loop is discussed. The proposed control theoretic view (block diagram in Fig. 1) includes all of the relevant algorithmic blocks mentioned above.

This is a cross-layer affair, because QoS is an issue on traffic flows defined on layer 3 [8], [9]. These flows are supported by a QoS capable packet scheduler in layer 2. It closely cooperates with the resource scheduler which itself decides on PhyModes using measurements of layer 1.

We conclude with results of the closed loop adaptive power control which aims at reducing the transmitted power level and therefore the neighbor interference.

A. Resource Scheduling

Resource scheduling (RS) is performed by the BS or RN on the assigned resources given by the resource partitioner. The resource scheduler consists of

- *resources:* as given by the partitioning [10],
- *subchannel capabilities:* by CSI/CQI [6],
- *subchannel assignment:* by DSA strategies [3],
- *PhyMode selection:* adaptively by AMC [11],
- *power allocation:* adaptively by APC [7],
- *other features:* dynamic segmentation, HARQ retransmission resources, SDMA beamforming and MIMO coordination etc.

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 [12]. Fortunately some of these tasks are almost orthogonal and therefore they can

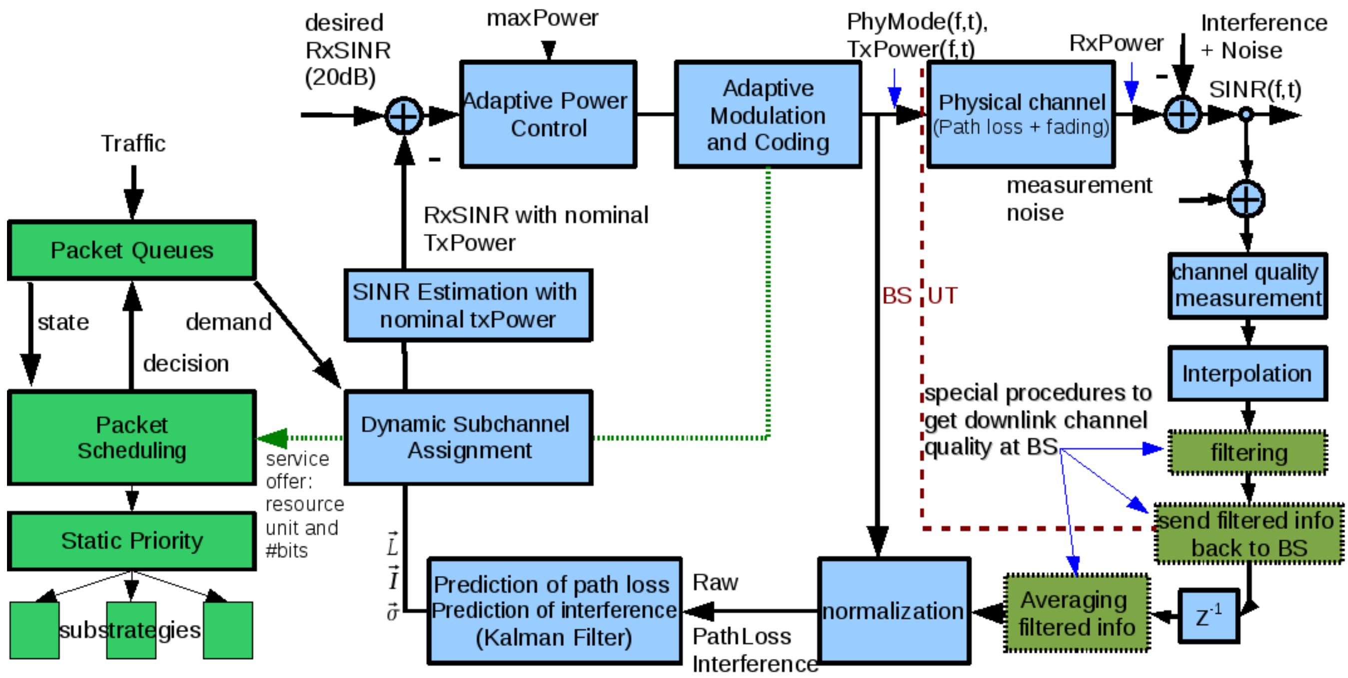


Fig. 1. Closed Loop Control view of the OFDMA DL resource scheduling tasks. The desired $SINR$ at the receiver is sufficient to support the highest possible LTE PhyMode. The packet scheduling tasks are shown in green to the left.

be solved step-by-step [2], [13]. In section II this stepwise approach is transformed into a block diagram view.

B. Packet Scheduling

The packet scheduler (PS) takes into account

- *traffic demand:* by the queue occupancies,
- *QoS demands:* by static priority mapping,
- *Fairness:* by fair strategies within a priority class,
- *other features:* buffer/overflow management etc.

A lot of literature exists on schedulers, so good and practical solutions exist. QoS support requires a connection or flow aware layer 2 [9], in order to distinguish multiple packet streams of different QoS class to one or more UTs. QoS class distinction is achieved by a static priority mapping and within one priority class there are scheduling substrategies adapted to the specific QoS needs: For best effort (data traffic) Round Robin (RR) [14] is often used, Proportional Fair is required in some situations [10] and deadline-aware scheduling is useful for realtime traffic QoS support [15].

II. A Closed Loop Control Model

Figure 1 shows the closed loop control block diagram, where the blocks perform actions independently and their dependency is only specified by their connections. Control block diagrams [16] take the reference value (desired $RxSINR$) on the left, and compare it with the estimated $RxSINR$ assuming that the nominal $TxPower$ is used for this subchannel. $20dB$ are requested because this 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 $\vec{SINR}$ 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 $\vec{SINR} = Rx\vec{Power}/(I+N)$. This is the controlled value (see above), because we want this value to be sufficient to support the highest PhyMode ($\geq 18dB$). 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. 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, 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 [5]. 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. Shown to the left (in green) is that the traffic demand limits the number of subchannels needed per UT. DSA interacts with the packet scheduling block at this point, because an assigned subchannel is a physical resource block (PRB) that defines the *amount of service* given to a traffic flow. The number of bits of this PRB is only known after the AMC decision has been taken, because the chosen PhyMode decides the capacity of this subchannel.

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). 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. 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).

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

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 (APC) block can increase or decrease the actual transmit power $P_{T,c}$ to achieve the desired $SINR$ level. We assume a piecewise linear control here (no quantization, no lower limit). There is of cource an upper limit inside, specified by $maxPower$ per subchannel c, because the power can only be adapted within certain bounds. Especially the limit $P_{max,c}$ is typically reached 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 $SI\vec{N}R$ is known on each subchannel and the AMC block will decide on the PhyMode given the link level results.

The Packet Scheduling (PS) task is shown linked to DSA here, because the best subchannels are chosen for certain UTs and flows [9] within. The PS knows the queue state (on DL) or the resource requests (on UL). Inside it keeps flows organized per priority which are scheduled within static priority levels where each level can have its own substrategy, as proposed in section I-B.

Figure 1 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.

III. Simulation Results

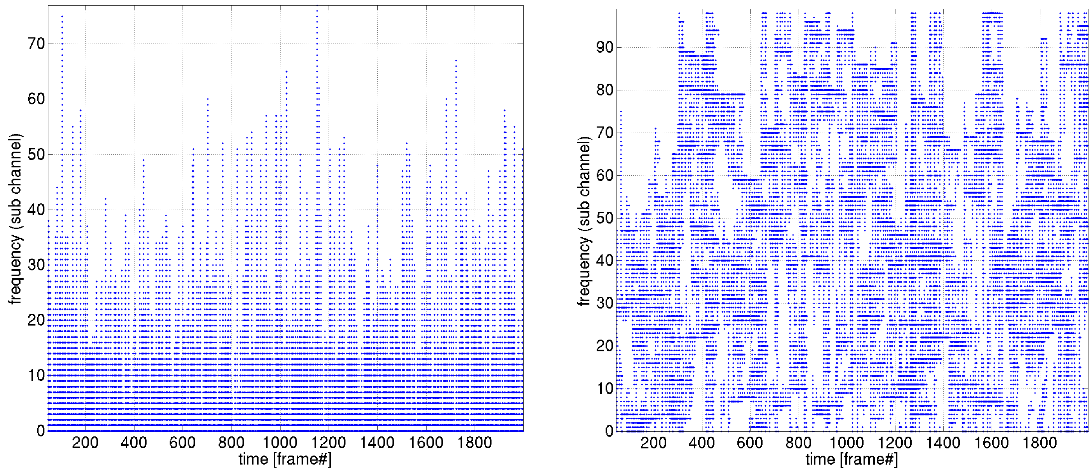
A cellular scenario with UTs in certain critical positions has been studied. The controlled system with all adaptive algorithms has been implemented in the OpenWNS system simulator [17]. The channel is fast fading with $10Hz$ doppler shift and almost no correlation between subchannels (worst case). There are two systems in comparison. System A 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 uses appropriate DSA, AMC, APC algorithms.

The outcome of two DSA strategies are shown in Figure 2 for a traffic load of 25%. Without CQI information the LinearFF DSA strategy simply selects the smallest subchannel numbers (Fig. 2(a)). The DSA “best channel” in Fig. 2(b) uses the potential of the whole bandwidth.

The next scenario emphasizes cell edge users ($d = 1600m$). Without correct CQI, Figure 3(a) shows that AMC selects one PhyMode ($QAM16 - \frac{5}{6}$), but many $SINR$ values are beyond the allowed bounds for this PhyMode. 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 3(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. 4(a)) and therefore reduces the interference into the neighbor cells. The APC result in Figure 4(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 4(a)) is now distributed symmetrically to the pathloss distribution pdf. Around $10dBm$ can be saved here that now do not interference into neighbor cells. Even higher gains are possible for UTs closer to the BS ($d < 768m$).

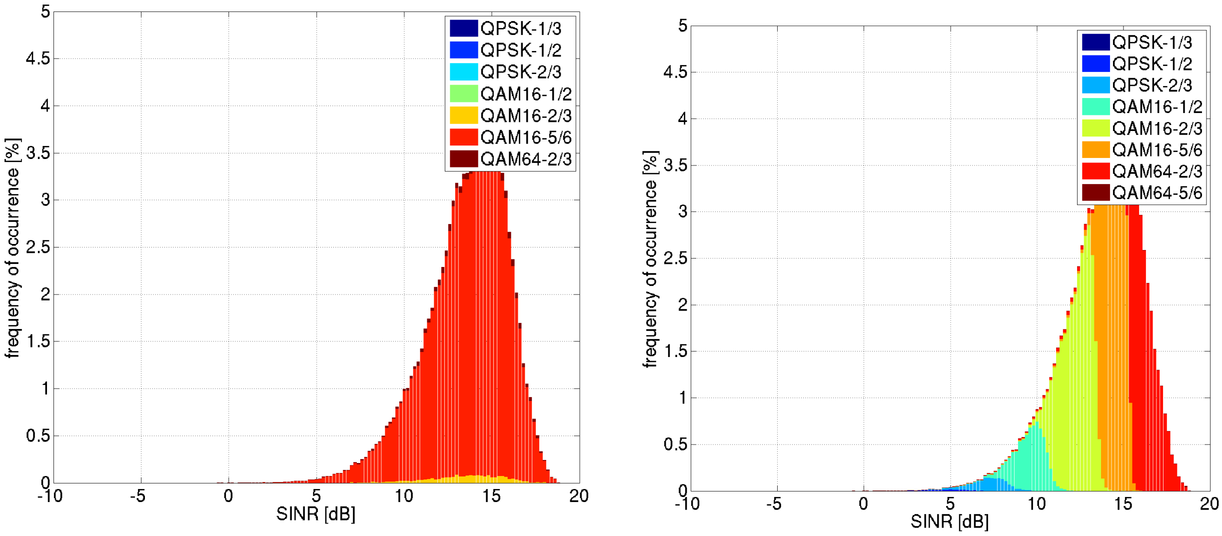
It is interesting to note that using APC makes AMC less necessary, because there is only one target PhyMode and power is controlled to achieve its optimum SINR. Both APC and AMC rely on correct CQI. If the fading is faster, both are expected to perform worse. For this case a higher SINR margin



(a) Scheduler with (simple) linear DSA strategy

(b) Scheduler using "best channel" DSA strategy

Fig. 2. Used DL resources in time and frequency with Dynamic Subcarrier Assignment strategies LinearFF and BestChannel. Distance = $768m$.



(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. 3. Probability density functions of the SINR at the receiver with and without CQI channel estimation data. Distance = $1600m$.

is recommended. Alternatively for ultra fast fading, a simple DSA strategy could just evenly distribute the subchannels to utilize transmit diversity [3].

IV. Conclusion

A closed loop control model for the OFDMA resource and packet scheduling tasks was presented in this paper. It contains all adaptive tasks as building blocks, e.g. Dynamic Subcarrier Assignment, Adaptive Modulation and Coding, Adaptive Power Control, Channel Quality Indication. From layer 1 to 3 this is a cross-layer affair due to the parameters that come from layers below and above layer 2. This model allows to handle the complexity of the system better and to study their dependency. The working simulator implementation with a scenario of a cellular 4G system proves the concept. The fast power control within one round-trip time is implicitly incorporated in this closed loop approach. Simulation results show the power reduction using APC. Future research will analyze more different block strategies and the spectral efficiency in multi-cellular scenarios.

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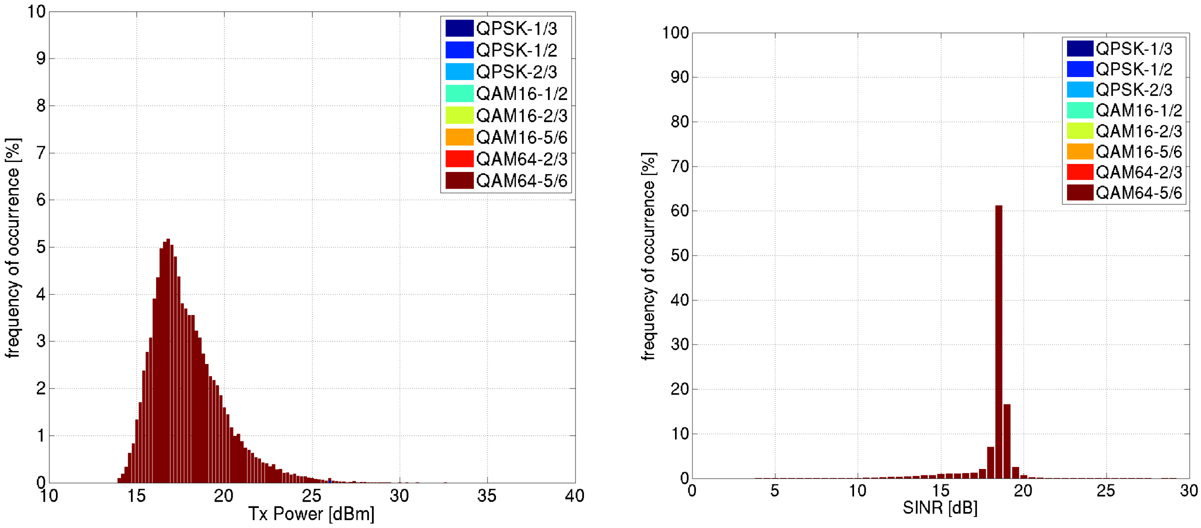

(a) Actual transmit power distribution using APC (controller output). The nominal power would be $26dBm$ per subchannel.

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

Fig. 4. Using Adaptive Power Control (APC) in DL: Transmitted and received power probability density functions. Distance = $768m$.

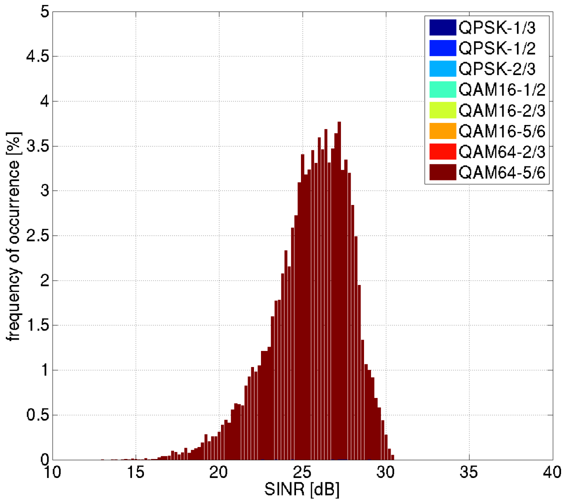

Fig. 5. SINR at the receiver without Adaptive Power Control (APC) at a distance = $768m$)

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