A Closed Loop Control Model separating Resource and Packet Scheduling in Multihop Cellular Networks

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***Abstract*—4G cellular systems and the IMT Advanced candidates will provide broadband wireless access with QoS. Especially in multihop configurations of these systems the base station controls resources centrally while relays can take over a part of the responsibility on the second hop. To make this work on layer two, scheduling is the most important task. However, many dimensions of the problem lead to much confusion. In this paper we approach this complexity inside the MAC layer. First, we propose that Packet and Resource Scheduling are two distinct tasks inside the medium access control layer of a wireless system. Due to the frequency selective channel and huge path loss ranges dynamic subcarrier assignment and adaptive power control are important. Proper resource scheduling also relies on accurate channel quality indication so there is a natural loop from base station to user terminal and back.**

Existing work and solutions see this as one single unit and end up in NP-hard problems or heuristics.

Instead we propose a closed loop control approach and show how almost independent building blocks fit into that system view. We conclude with adaptive power control results.

***Index Terms*—Scheduling, Closed Loop Control, DSA, APC**

I. Introduction

SCHEDULING in wireless systems refers to the way communication requests (packets, PDUs) are assigned to use the available radio resources. This is a typical task on layer 2 in the ISO-OSI model and a lot of literature exists for all kinds of scheduling. For classification purposes let's clarify the confusion between packet and resource scheduling. 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. This is like a queueing system where the server consists of two parts, one decides *who* will donate the resources and the other *how* to spend them. In this paper we further subdivide these tasks by proposing a block diagram for the many issues of resource scheduling. The separated packet scheduling is then done similar to QoS support in wired networks.

In all modern systems with IP traffic and OFDMA channel usage the demand is variable and the channel is variable over time and frequency due to multipath fading. There are also orders of magnitude for the path loss 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]. The algorithms therefore must be multihop capable.

Since the path loss 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. The following view and focus of the paper is on the layer 2 system perspective, so an abstraction is made of the physical layer.

In the operating region for signal-to-interference+noise ratios of $SINR = 0..20dB$ OFDM systems typically adapt the Modulation and Coding Scheme (MCS), also called PhyMode. Figure 2 shows the available LTE PhyModes and indicates switching points. 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.

Another important task of resource scheduling is the Dynamic Subcarrier Assignment (DSA) [3]. For multihop systems, this task requires resource partitioning (RP) before [4], [5]. DSA requires channel state information (CSI) which is signaled as channel quality indication (CQI).

An optional Adaptive Power Control (APC) unit regulates the output power of each transmitted subchannel selectively in frequency and time [6]. It compensates for the fading notches in the short-term and for the distance-caused path loss imbalance between UTs in the long term.

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

By studying the input and output values of the blocks and their precedence, using background knowledge of control theory, the original problem of utilizing the wireless channel can now be seen much simpler. This also simplifies the implementation, e.g. in the C++ simulator model [7]. By this way experts can now focus on each building block alone instead of trying to solve everything in one monolithic block.

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

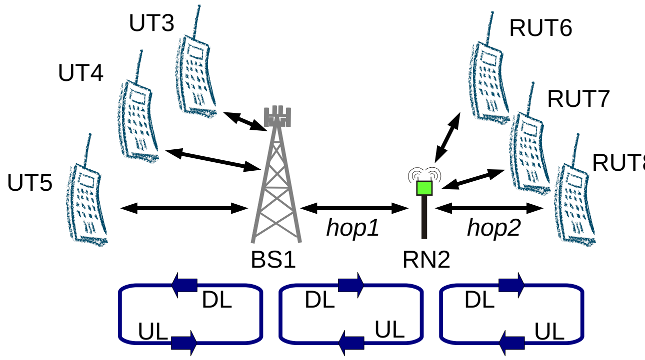


Fig. 1. LTE multihop scenario with 1BS, 1RN, 3UTs and 3RUTs

II. Resource Scheduling

Figure 1 shows a typical multihop FDD scenario. Full and half duplex terminals are supported [4]. As one candidate of the IMT-Advanced family LTE-Advanced is assumed here. Each TTI frame is limited in time ($500\mu s$) and frequency (100 subchannels = 1200 subcarriers for the bandwidth $B = 20MHz$). The available subchannels define the resource blocks available for scheduling.

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. $UT \rightarrow BS$, $UT \rightarrow RN$, $RN \rightarrow BS$.

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 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 single cell coordination in time and frequency is assumed, while the neighbor cell activities (neighbor cell resource usage) are treated as uncontrollable 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 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.

A. 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 takes into account

- *resources:* as given by the partitioning [5],
- *subchannel capabilities:* by CSI/CQI [8],
- *subchannel assignment:* by DSA strategies [3],
- *PhyMode selection:* adaptively by AMC [9],
- *power allocation:* adaptively by APC [6],
- *other features:* dynamic segmentation, HARQ retransmission resources, SDMA beamforming and MIMO coordination etc.

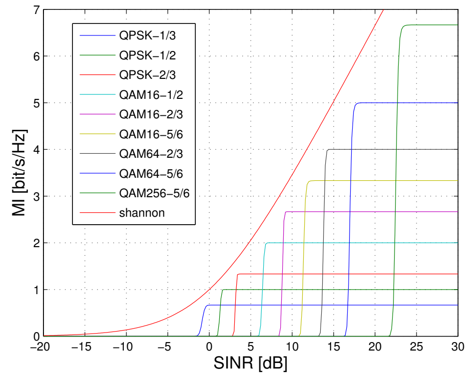


Fig. 2. Link level results for different modulation&coding schemes (PhyMode) [9]. $QAM256$ is extrapolated and not part of the LTE standard.

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 [10]. Fortunately some of these tasks are almost orthogonal and therefore they can be solved step-by-step [2], [11]. In section III this stepwise approach is transformed into a block diagram view.

B. Packet Scheduling Tasks

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 [12], 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) [13] is often used, Proportional Fair is required in some situations [5] and deadline-aware scheduling is useful for realtime traffic QoS support [14].

C. Multihop Scheduling

In a multihop cellular network a relay node (RN) performs just like a BS towards its remote UTs (RUT) and incorporates all RS and PS functionality, except that it operates on a subset of resources given by the BS during the resource partitioning [5]. Towards the BS a RN acts like another UT, except that it handles the aggregated set of flows. This means the BS resource scheduler allocates resource blocks for the first hop transmission based on the DL demand in its queues and the UL resource requests from the RN. The BS packet scheduler is aware of all flows, so that it can distribute the service among all competing flows according to the static

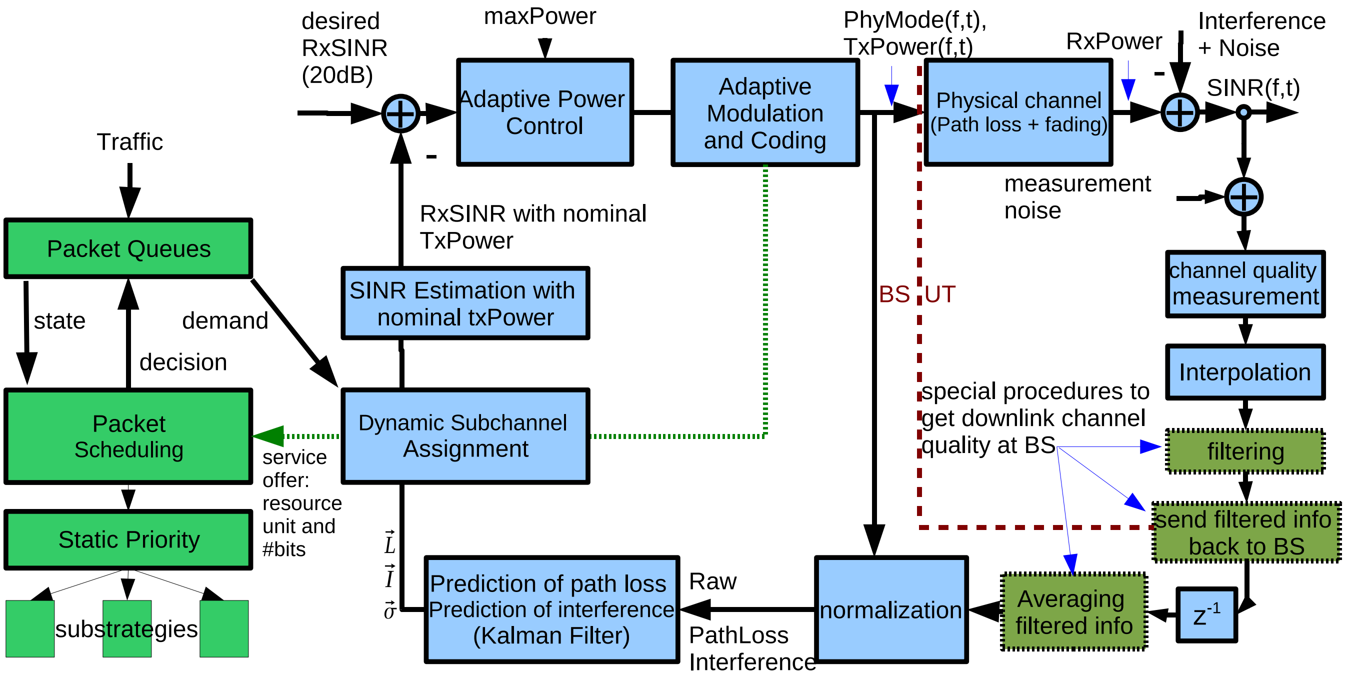


Fig. 3. Closed Loop Control view of the OFDMA DL resource scheduling tasks. The desired $SINR$ at the receiver is sufficient to support the highest possible LTE PhyMode (Fig. 2). The packet scheduling tasks are shown in green to the left.

priority and substrategy concept [12]. A balanced resource partitioning for the first and second hop is required in order to avoid congestion either in the DL or UL while being relayed from the primary to the secondary transmission.

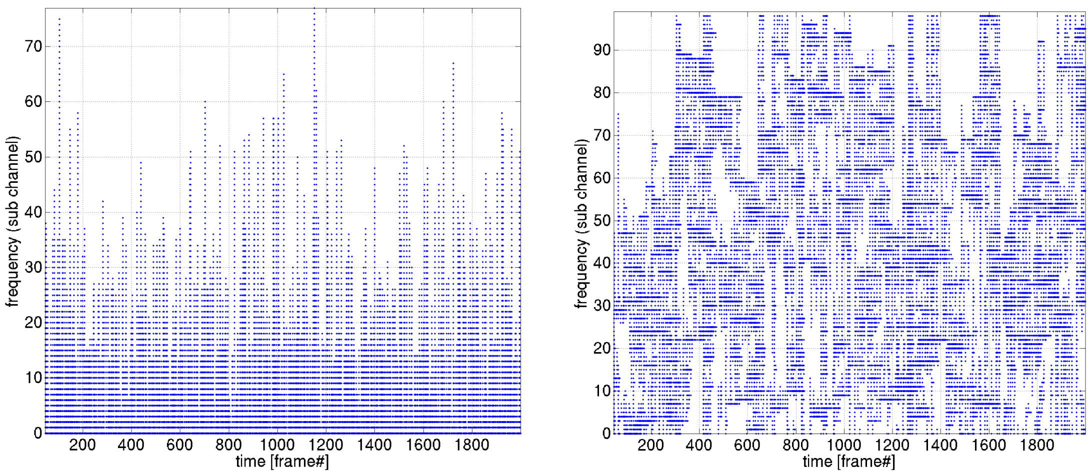
III. Closed Loop Control

Adaptive OFDMA resource scheduling requires algorithms for subchannel, PhyMode and power selection. At the first glance the decisions look like they are not independent, but with the proposed block diagram view it comes to a natural order of execution. Figure 3 shows the closed loop control block diagram. Control block diagrams [15] 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. $SINR_{desired} = 20dB$ are requested because this supports the highest LTE PhyMode $QAM64 - \frac{1}{2}$. $RxS\vec{I}NR$ 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. The red dotted line is the separation between transmitter and receiver side. 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.

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 $\vec{P}_R = Rx\vec{P}ower$ at the receiver. Interference and noise power is subtracted here to get the $SI\vec{N}R = Rx\vec{P}ower/(I + N)$. 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. 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 $Rx\vec{P}ower$ and $SI\vec{N}R$ of course depend on the transmitted power level per subchannel $\vec{P}_T = Tx\vec{P}ower$, 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



(a) Scheduler with (simple) linear DSA strategy

(b) Scheduler using "best channel" DSA strategy

Fig. 4. Used DL resources in time and frequency with Dynamic Subcarrier Assignment strategies LinearFF and BestChannel. Distance = $768m$.

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 [4]. 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 (Fig.2).

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).

$$SINR_{nominal,c} = \frac{P_{T,nominal} \cdot L_c}{I_c + N} \tag{1}$$

The controller then compares the nominal $SINR$ with the desired $SINR$ ($\oplus$ block) and depending on sign and amount of the difference, the adaptive power control (APC) block increases or decreases the actual transmit power $P_{T,c}$ to achieve the desired $SINR$ level.

$$\frac{P_{T,c}}{dBm} = min(\frac{P_{T,nom}}{dBm} + \frac{SINR_{des} - SINR_{nom,c}}{dB}, \frac{P_{T,max}}{dBm}) \tag{2}$$

We assume a piecewise linear control here (no quantization, no lower limit). There is of course an upper limit inside, specified by $P_{T,max}$ per subchannel c, because the power can only be adapted within certain bounds. Especially the limit $P_{T,max}$ is typically reached for UTs at the cell border. There is also a global maximum power $P_{T,max,total}$ which is given by the RF amplifier and EIRP limit regulations.

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.

The Packet Scheduling (PS) task is shown linked to DSA here, because the best subchannels are chosen for certain UTs and flows [12] 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 II-B. The DSA block only needs to know the number of bits waiting in the queues per flow (the $demand$). DSA knows about priorities of the flows (from the flow management unit) and takes it into account when assigning resources for UTs. Once the DSA result is known (which resources occupied by which flow) and the PhyMode is fixed for these resources (green dotted line) this information (the $serviceoffer$) is provided to the packet scheduling unit. It can then take decisions on the order of packets according to substrategies. The decision commands the packet queues to output the segmented packet, which is then put into the resource elements (not shown).

Figure 3 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

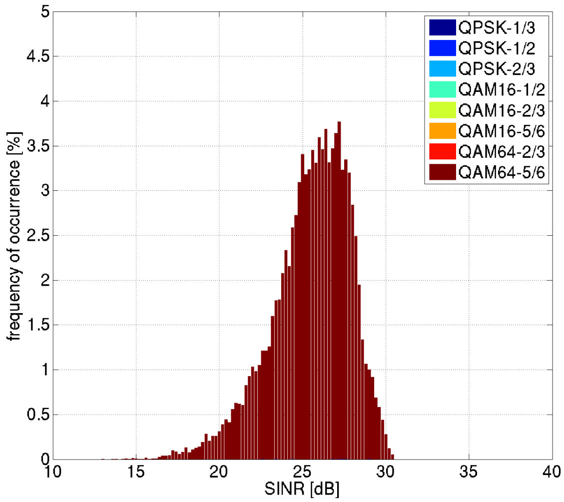


Fig. 7. SINR at the receiver without Adaptive Power Control (APC) at a distance = $768m$)

signaled to the UTs.

IV. Simulation Results

The controlled system with all adaptive algorithms has been studied using the OpenWNS system simulator [7]. The scenario was a cellular environment as in Fig. 1. 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 4 for a traffic load of 25%. Without CQI information the "LinearFF" DSA strategy simply selects the smallest subchannel numbers (Fig. 4(a)). The DSA "best channel" in Fig. 4(b) uses the potential of the whole bandwidth.

The next scenario emphasizes cell edge users ($d = 1600m$). Without correct CQI, Figure 5(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 5(b).

At a shorter BS-UT distance ($d = 768m$) the $SINR$ is much more than sufficient (Figure 7). 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. 6(a)) and therefore reduces the interference into the neighbor cells. The APC result in Figure 6(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 6(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 is recommended. Alternatively for ultra fast fading, a simple DSA strategy could just evenly distribute the subchannels to utilize transmit diversity [3].

V. Conclusion

This paper treated the scheduling aspects in a mobile radio system. The OFDMA resource and packet scheduling tasks are discussed. A closed loop control model is introduced which contains all adaptive tasks as building blocks, e.g. Dynamic Subcarrier Assignment, Adaptive Modulation and Coding, Adaptive Power Control, Channel Quality Indication. This model allows to handle the complexity of the system better and to study their dependency. The working simulator implementation 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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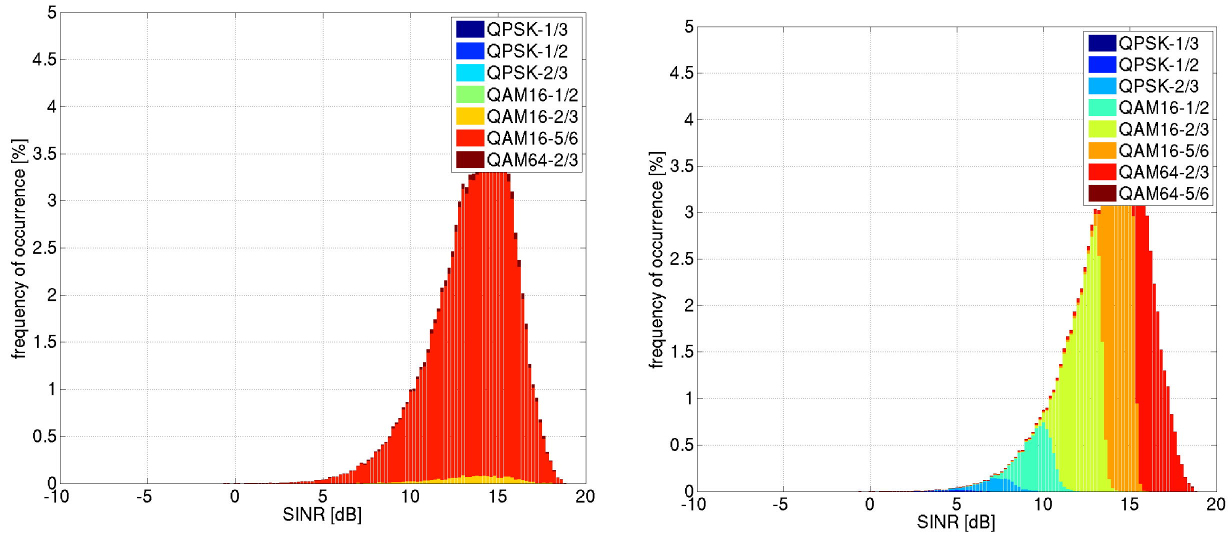
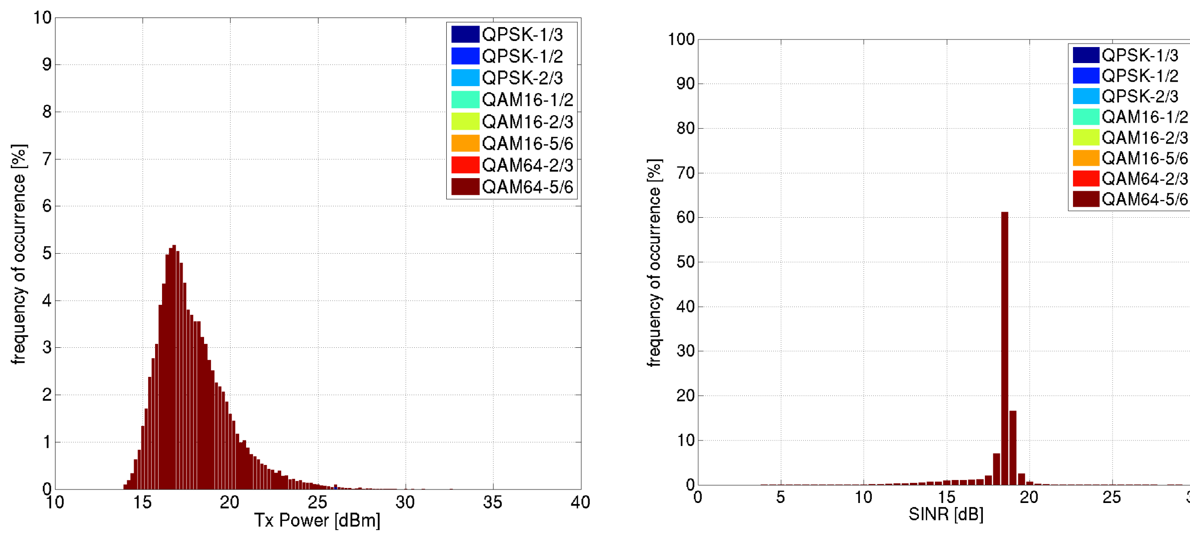


(a) Scheduler without CQI information (flat channel assumption). AMC decides one PhyMode only

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

Fig. 5. 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



(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. 7.

Fig. 6. Using Adaptive Power Control (APC) in DL: Transmitted and received power probability density functions. Distance = $768m$.

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