Channel Quality Indication for Adaptive Resource Scheduling in Multihop OFDMA Systems

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Abstract—IMT-Advanced systems of the future will be based on OFDMA and frequency division duplex will be widely used. Multihop techniques, e.g., the use of fixed relays, are also considered a key technology. The OFDMA resources have the dimensions time, frequency and space. In all these dimensions a radio channel is variable due to fading. On the other hand a complete utilization of the channel capacity close to the Shannon bound is required. Therefore all channel adaptive modulation and coding schemes require good channel state information. For FDD this needs to be signalled back from user terminals to base stations or relays, so that the adaptive scheduling algorithms there can decide optimally. This is performed by channel quality indication. This paper discusses a multimode-capable multistage CQI concept for IMT Advanced systems, shows measurements from simulation and provides the system view including CQI.

Index Terms—CQI, CSI, OFDMA, FDD, Relaying, Multihop

I. INTRODUCTION

IMT Advanced systems in the future will support high data rates in cellular systems. Candidate technologies are LTE-Advanced [1] or WiMAX [2], but also the Wireless World Initiative New Radio (WINNER) system design [3] provided reference designs. All future systems are based on OFDM transmission an OFDMA multiple user access to optimally utilize the radio resources. These system concepts also includes Multihop relaying [3]–[6]. The channel duplex scheme is FDD in many systems, even if pros and cons compared to TDD are ambivalent [7]. FDD requires operation of two distinct physical channels for transmitting downlink (DL) and uplink (UL) frames at the same time while TDD operates on one channel only where DL and UL phases are interleaved in time. This implies that for FDD the channel quality is only known on the receiver side, while for TDD the symmetry and reciprocity of the channel often can be used.

In cellular systems, the base station (BS) controls all resources for the radio cell. For Multihop operation, it can delegate a subset of these resources towards relay nodes (RN) [8]. This is the resource partitioning task for which solutions have been proposed [9], [10]. Scheduling and frame timing in multimode is most complex in Half-Duplex-FDD [11]. Anyway the BS scheduler for DL needs channel state information (CSI) signalled via channel quality indication (CQI) from the user terminals (UT). For the uplink, the CSI is simply taken from its own reception.

The process of generating the CSI from the measurements in the PHY layer to the CQI report in the MAC layer consists of steps explained in this paper. The second half is the processing of the CQI report in the BS. This also requires steps to interpolate and extrapolate (predict) into the future, as discussed in this paper. The bottleneck for CSI is the CQI signalling which must be at a low rate so that the overhead on the UL is not too high, but requires a high rate to be accurate. Some proposals exist to reduce the signalling overhead. In this paper a generic model is proposed in order to allow the use of all CQI, scheduling and control algorithms.

The paper is structured as follows. Section II defines the concept of the CQI and CSI algorithms. In Section III the multihop OFDMA system including CQI is discussed with results of resource scheduler algorithms. The paper ends with a concluding summary.

II. CHANNEL STATE INFORMATION

FDD systems use 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 in case of a multihop system. The lower band is used for the uplink (UL), i.e. $UT \rightarrow BS$, $UT \rightarrow RN$, $RN \rightarrow BS$. Figure 1 shows the timing in an LTE superframe.

The timing organization of the superframe and scheduling of the resources of each frame is performed by functional units of the MAC layer in the BS. Before each transmit and receive block there needs to be a signalling of resources that will be used, called a map. This map is sent from $BS \rightarrow UT$, $BS \rightarrow RN$, $RN \rightarrow UT$ immediately before the data part of the TTI frame [12]. The map contains the results scheduling of the scheduling process for the DL and UL. The scheduler itself performs resource and packet scheduling separately [8]. The resource scheduler requires CSI to perform its dynamic subcarrier assignment (DSA) task. This calls for CQI signalling from UTs to the BS.

A. Channel Selectivity and Measurements

In broadband OFDM transmission systems the channel is highly selective in frequency domain and also time variant (Figure 2). The coherence between neighbouring subchannels and between adjacent time frames mainly depends on the mobility of the user terminal, i.e. Doppler frequency and delay spread. The channel is typically not known implicitly, especially for FDD where DL and UL are separated in frequency. But for the optimal utilization of the DL and UL channel an adaptation to the channel state condition must be performed. Adaptation means to do Frequency Selective Scheduling (FSS)
or more precisely Dynamic Subcarrier Assignment (DSA), Adaptive Modulation & Coding (AMC) and Adaptive Power Control (APC) [8].

In order to know the channel state for each resource element, an estimation has to be done based on past values which are fed back from the receiver. In the UL, the receiver is already in the same unit (BS or RN) where the PhyMode (modulation & coding scheme) decision is taken. For the DL, this feedback is performed by using channel quality state and indication (CQI). In the multihop case, RNs contain both elements, those of a BS and of a UE. The mechanisms to achieve this are explained now.

The measurement of the channel condition is based on received input signals either from data packets or from pilot symbols. Both can be thought of suitable ways to get the information. In general, the pilots are equally distributed in time and frequency, so they provide the most complete picture, while the packets offer more power, so the measurement is more reliable. The CQI information can contain those values per subchannel:

- the received signal power ($P_{Rx}$),
- the received interference + noise level ($I + N$),
- the received SINR level ($SINR$),
- the received mutual information value ($MI$),
- the estimated path loss ($L_P$),
- and maybe some confidence values to specify the accuracy of the measurement.

The item $P_{Rx}$ is available due to pilot measurements and also the output of the Viterbi decoder can deliver useful support data. Also the $I + N$ can be determined in the PHY layer of the receiver. The interference estimation is a powerful tool to support interference coordination/avoidance in BSs. The $SINR$ is redundant as $SINR = 10 \log_10(P_{Rx} / (I + N))$ and can be calculated when needed from the values above. The mutual information $MI$ is a measure of the expected channel capacity [14] and can be used to verify the correctness of the chosen PhyMode, because the packet error rate (PER) can be calculated from it ($MI = f(SINR, PhyMode)$). In the end we are interested in the path loss value ($L_P$) only, because the sender knows its transmit power ($P_{Tx}$) per subchannel, which may be variable over time and frequency with APC, so only the $L_P$ is quasi constant and independent of the $P_{Tx}$.

B. State of the art

Frequency Selective Scheduling is proposed by many research papers [15] and there are many ways to perform it [16], [17]. Channel Measurements are in most cases mentioned in the CQI context [18], [19]. Channel Quality Indication is mentioned in some literature [20] but is quite a new topic and far from comprehensive. Some assessments have dealt with the topic of CQI efficient reporting in EUTRA. In [21] several schemes to reduce the CQI overhead are presented (exhaustive reporting, average reporting, best-M reporting, etc.) and its
impact on frequency selective scheduling is measured. Similar assessments are found in [22], [23]. In other assessments, in addition to the limitation in the feedback information, this information is compressed [24].

C. CQI in the LTE standard

In OFDMA systems such as LTE, FSS significantly improves system performance. Depending on the CQI bandwidth used, explicit CQI feedback for every resource block (RB) can result in significant overhead and therefore reduced capacity. However, the overhead is in the UL while the performance benefit is on the DL, which makes the assessment ambiguous.

3GPP had been studying the design of the CQI reporting to define the procedure to be used by Rel.8 [25]. In this draft standard, the CQI table is composed of 16 entries (CQI is 4 bits per filtered subchannel). The CQI table entries are defined as an index to the suggested PhyMode. A UT reports a CQI index corresponding to a transport format with 10% BLER target at the first transmission, over the set of resource blocks corresponding to the CQI value. However, as a drawback, the UT decides on the PhyMode and there is no provisioning for APC, since the UT cannot know the $P_{TX}$.

The eNodeB controls time and frequency resources used by the UT to report CQI and the report timing can be periodic or aperiodic. The UT transmits CQI reporting on the PUCCH for subframes with no PUSCH transmission and on the PUSCH for those subframes with scheduled PUSCH transmissions. The CQI methods main candidates presented by the 3GPP partners were the following [26]:

- Wideband CQI (Flat channel assumed)
- All RBs (Reference Case)
- Best-M: CQI for each indicated (1 CQI each of M-Best)
- Best-M-A: Average CQI indicated (1 CQI that averages all the M-Best)
- Hierarchical: indicate average CQI for selected level where each level represents a sub-band
- DCT (Discrete Cosine Transform) based

The three reporting methods selected were: Wideband CQI, Higher Layer-configured sub-band feedback and UT-selected subband feedback (best-M algorithm).

D. The Proposed CQI concept

The measurement of the channel condition is based on received input signals either from data packets or from pilot symbols. Both can be thought of suitable ways to get the information. Using pilot symbols provides measurements for the whole bandwidth. Measurements from packets only provide limited information on the used subchannels, which is especially bad when the traffic is very low and few subchannels are used only. The scheduler wants to have as much information as possible, if required. For a simulation study using the OpenWNS simulator [27] the complete information should be available. This allows to study of resource schedulers which utilize this information. For standards and production, a simplified approach should be taken.

Figure 3 shows the processing steps. The CQI information includes the values of section II-A. Incomplete knowledge (holes in the 2D data) must be inter- and extrapolated to have the full picture. For the simulation purpose this is done immediately after the measurement. After this step the full CQI is available (still at the receiver) for every point in time and frequency.

The next step is the reduction of CQI data to reduce signalling overhead. This step is called filtering. It selects a subset of the full CQI information and prepares it for signalling from the receiver back to the transmitter (UL signalling for DL measurements). An example is the Top-M strategy selecting the best M subchannels. For the UL this is not necessary. The BS can use the complete measured data in the UL without signalling.

Quantization (more generally: source coding) is a task after filtering. This means the floating point value for a power level is mapped to a limited number of discrete integer values, e.g. 0..15, so that a compact transport is possible within a signalling message. For performance evaluation purposes this is optional and the effects of limited feedback can be studied. The limited signalled data is received in the BS. There it is necessary to reconstruct the original data again to have a CQI value for each subchannel. This again is an inter-/extrapolation step. The result is a full CQI matrix again, however a little bit outdated due to measurement and signalling latency.
Therefore a last step called prediction is necessary. It tries to estimate the CQI values for the future, i.e. the position in time it is needed for, which is the next time slot or frame the resource scheduler calculates the dynamic subcarrier assignment for. Depending on the latency of the scheduler and the scheduling map, which must be sent prior to the DL data, the originally measured data can be outdated/delayed for up to 3 TTI frames. The prediction tries to compensate this and can add additional safety margins, in case the information is unreliable. At the BS, the CSI information itself should contain at least the estimated path loss \( L \) and interference level \( I + N \). It is important not to use the received power level \( P_{Rx} \), because this might have been influenced by transmit power control (adaptive power allocation, APA). Given the path loss, the power control unit of the scheduler can itself calculate with which \( P_{Tx} \) it must send on a subchannel, so that a suitable SINR is achieved at the receiver. The interference level measurements per subchannel can be used in the dynamic subcarrier assignment process, to avoid heavily interfered parts of the spectrum (interference mitigation).

### III. The Use of CQI in an LTE System

Once the CQI information is known, the resource scheduler can utilize it to predict the future. A prediction unit handles the incoming CQI and proposes an estimation/prediction into the future, so that for each frequency and time resource unit there is a value for the channel state. After some calculations an SINR estimation for each subchannel is known, which can be used to choose the best subchannel, adapt PhyMode, and even to adapt the power allocation on this subchannel.

The link adaptation (modulation, coding, power and hybrid ARQ parameters) is done based on the CQI reports. Usually, in this process it is employed by a mapping function to predict the link performance (in terms of bit error rate, block error rate or similar indicator [14]) given a combination of adaptable parameter values and an experienced channel quality.

A CQI-inaccuracy-aware resource allocator could enhance the performance of an adaptive system. For example the CQI confidence values (from a Kalman filter) could be used. So the prediction algorithms reduces the effect of the CQI error.

In many assessments conducted over 3G or B3G technologies several constraints are posed to the operation of the link adaptation mechanism. For example, power is distributed uniformly per resource unit or the same modulation and coding scheme is employed for all the information of the same transmission resource. If we allow the power to be controlled we gain the additional option of a closed loop control. The control block diagram of the OFDMA link is shown in Figure 4 [8]. 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. The SINR value is measured at the the receiver and all the proposed CQI blocks of Figure 3 appear here again as parts of the control loop. 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 \( L_P = P_{Rx}/P_{Tx} \) as quotient between received and transmitted power. 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. Figure 7 shows the CQI information and the resulting DSA output for an offered load of 50% and a UT distance of 1000m. Figure 6 shows the result of the AMC step (the assignment of PhyModes given the SINR estimation) but with the real SINR at the receiver.

The message sequence chart in Figure 5 shows the timing behaviour of the CQI messages. The three actors are BS, RN and one UT. The CQI-Handler in the BS receives DL-CSI by CQI signalling and the UL-CSI by directly measuring. There is no signalling between remote UTs (associated to a RN) an the BS. In the multihop case the RN itself acts as a BS. It therefore receives CQI messages itself and performs FSS upon these values given the subset of resources assigned to the RN via partitioning [8].

### IV. Conclusion

This paper presented a concept for the processing steps of Channel Quality Indication and the subsequent scheduling units. Especially for future FDD systems a reliable and power-independent Channel State Information is required to allow the optimum use of the Frequency Selective Scheduling algorithms. We therefore propose to supply only the pathloss and
interference power value per subchannel to the scheduler. This allows the flexible use of all adaptive algorithms, presented in a closed loop control system model.

Future research should investigate into detail the possible methods at each of the CQI steps, together with its consequences for the scheduling algorithms DSA, AMC and APC. Also an interference mitigation using the reported interference levels is now possible.

REFERENCES


Fig. 7. Left: The predicted pathloss supplied to the scheduler [dB]. Right: Scheduled resource usage: Each dot means a used resource block.