Efficient Allocation of CQI Channels in Broadband Wireless Networks

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Abstract—**In an OFDMA network, the modulation and coding scheme (MCS) of the messages sent to the mobile stations (MSs) varies according to channel condition. To determine the appropriate MCS level, the base station (BS) allocates to every active MS a CQI (Channel Quality Information) channel. The CQI bandwidth is a scarce resource whose allocation must be adjusted to the actual needs of the MSs. However, allocations and deallocations of CQI channels require expensive signaling messages between the BS and the MSs, and therefore should be minimized. In this paper we propose a framework for the management of the CQI bandwidth by the BS. We identify three related optimization problems and propose efficient algorithms for solving them.**

I. INTRODUCTION

Communication over a time-varying wireless channel is subject to radio impairments, such as additive white Gaussian noise (AWG), flat and frequency-selective fading, and log-normal shadowing. These impairments introduce error and losses in the received information and degrade the quality of the delivered service. Moreover, when the radio channel quality degrades beyond a certain point, no communication is possible at all. But, when the radio channel is very good, bandwidth resources can be consumed more efficiently. For mobile hosts, both scenarios can take place at different times.

It is well known that different applications require different quality of service (QoS) levels. To ensure that the QoS requirements of each application are met under varying channel conditions, advanced wireless technologies, such as 3GPP/LTE [1] and WiMax/802.16 [6] adjust the modulation and coding scheme (MCS) for every frame to the wireless channel condition of the intended receiver. When the channel is good, a more efficient but less robust MCS can be used. When the channel is bad, a more robust but less efficient MCS should be used. To help the base station (BS) determine the appropriate MCS, every mobile node measures its channel quality and sends channel quality information (CQI) to the base station.

Both 3GPP/LTE [1] and WiMax/802.16 [6] support periodic and aperiodic CQI feedback. While aperiodic CQI feedback require the BS to send a signaling message each time it wants to receive a CQI report from an MS, periodic CQI feedback require only one signaling message for the allocation of a CQI channel and one for its release. The allocation message indicates the location and periodicity of the CQI channel slots. Once a CQI channel is allocated, the mobile node transmits CQI feedback messages on the slots of this channel until it receives a deallocation message.

This paper addresses the allocation of periodic CQI channels by the BS, and its contribution is twofold. First, to the best of our knowledge, this is the first paper that presents a formal framework for the allocation of periodic CQI channels. Second, it defines, again for the first time, several problems related to this framework and presents efficient algorithms for solving them.

The rest of this paper is organized as follows. In Section II, we discuss related work. In Section III, we show how to allocate CQI channels using a complete binary tree, in order to guarantee an efficient collision-free allocation, and describe the considered CQI channels allocation model. Section IV is the core of the paper. It defines the CQI allocation problems and presents efficient algorithms for them. Section V shows some simulation results.

II. RELATED WORK

Previous works have addressed aspects of the problem other than the one we address here. For example, with the exception of [9] and [13], previous works have not attempted to adjust the periodicity of the CQI reports to the specific needs of each MS. Rather, they have tried to reduce the cost of the CQI reports by: (i) not sending CQI reports if the channel condition has not significantly changed [2], [4], [5], [7], [10], [12]; (ii) sending a single CQI report to a group of MSs [8]; or (iii) sending a single CQI report for a subset of OFDM subchannels [10], [11]. All these works are orthogonal to the scheme and algorithms presented in this paper.

Schemes that make a decision not to send a CQI report due to (i), (ii) or (iii) above cannot easily take advantage of the unused slots. This is because these slots are too short for regular packets and because the MS cannot rely on their availability. The approach taken in this paper is different in the sense that the BS allocates CQI channels of different bandwidth to different MSs in accordance with each MS's individual profit function. Moreover, using the scheme proposed in this paper, the BS can view the CQI bandwidth as a shared resource, which is dynamically allocated to the various MSs. The BS can also adjust the size of this resource: when it realizes that it is too scarce, it can increase the total CQI bandwidth; when there are not so many dynamic MSs in its cell, the BS can reduce the total CQI bandwidth and use it for other purposes.

In [9], [13], the authors propose a CQI allocation scheme for 802.16. Their scheme views the CQI bandwidth as "toy brick." In contrast to these works, we represent the CQI bandwidth as a binary tree, which allows us to minimize the number of changes for allocating a CQI channel when the available CQI bandwidth is fragmented. We also allow different MSs to have different profit functions and seek to optimize the total profit of the BS. Moreover, we formally define the various related problems as optimization problems and analyze their complexity. Finally, we present optimal algorithms for the problems that are not NP-hard.

III. PRELIMINARIES

A. CQI channels

CQI is a part of the fast feedback region of the OFDM frame [6], and is used by the MSs to transmit channel quality information to the BS. The BS performs link adaptation and selects an appropriate MCS for the transmission to the MSs using the channel quality information it receives from each MS. The CQI bandwidth is divided into several super-channels. A super-channel consists of one slot in every uplink frame. The number of such super-channels is equal to the number of CQI slots in every frame. Each super-channel is divided into multiple CQI channels. This paper presents algorithms for such a division. To allocate a CQI channel, the BS sends to an MS a control message that indicates the following parameters:

(a) The sequence number of the first frame that contains a slot of this channel.
(b) The number of frames τ between two consecutive slots of this channel.
(c) The time during which this CQI channel is allocated to the MS. (Another option for the BS is to allocate the channel with no expiration time, and then to explicitly request it back.)

A CQI channel allocated to MS_j is denoted $\alpha_j|\tau_j$, where α_j is the sequence number of the first frame that contains a slot of this channel and τ_j is the periodicity of this channel. A smaller value of τ_j means more frequent CQI reports, which provide the BS with more accurate information about the channel quality of MS_j. However, if τ_j is too small, the BS is likely to receive too many identical CQI reports unnecessarily. Therefore, the optimal value of τ_j depends on the stability of the channel, which is affected by many factors such as:

(a) The mobility speed of MS_j.
(b) Physical obstacles and weather conditions.
(c) Interferences from other BSs/MSs and other wireless networks.

B. Power of 2 allocation

A power of 2 CQI channel allocation is an allocation for which $\tau = 2^i$ holds for every channel, where i is an integer between 0 and C. Such an allocation is useful because it can prevent collisions between two different CQI channels.

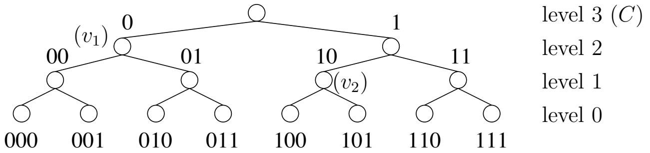

Fig. 1: An example of a labeled CQI allocation tree for a super-channel

Definition 1: Two or more CQI channels are said to collide if they contain the same slot. In other words, a collision occurs between $\alpha_1|\tau_1$ and $\alpha_2|\tau_2$ if for some integers $x > 0$ and $y > 0$, $\alpha_1 + \tau_1 \cdot x = \alpha_2 + \tau_2 \cdot y$.

We now show how a power of 2 allocation can be performed when the bandwidth of each super-channel is maintained using a complete binary tree T_C whose height is C. We refer to such a tree as a *CQI allocation tree*. Then, we shall see how such an allocation can be guaranteed to be collision-free. The leaves of T_C are in level 0, their parents are in level 1, and so on. We assign a label to every tree node in the following way. For a node in level l, the assigned label consists of $C - l$ digits from which the first $C - l - 1$ are the same as of the node's parent and the last digit is set to 0 for a left child or to 1 for a right child. Fig. 1 gives an example.

Let r be the reversed label of node v in the tree, and $d(r)$ be the decimal value of r. Then, node v is associated with the CQI channel $d(r)|2^{C-l}$. For example, node v_1 in Fig. 1 is associated with the CQI channel $0|2$, while node v_2 is associated with the channel $1|4$. We now prove that if each root-to-leaf path in the allocation tree has at most one allocated node, then the CQI channels represented by the tree do not collide. For example, consider the two trees in Fig. 2 and suppose that the black nodes indicate allocated CQI channels. In both trees there is at most one allocated node on every root-to-leaf path. By the lemma below, this indicates that the CQI channels represented are collision-free. The fraction near every black node indicates the fraction of the super-channel bandwidth assigned to the corresponding CQI channel.

Lemma 1: Two nodes of a CQI allocation tree are on the same root-to-leaf path if and only if their corresponding CQI channels collide.

CQI channel fragmentation is defined as the case where an MS is allocated 2 different tree nodes. For example, the allocation of $0|16$ and $1|4$ to the same MS is translated to the allocation of CQI slots as shown in Fig. 3. We can see that the slots are not uniformly distributed along the time axis. This is a suboptimal allocation because some of the slots are too close to previous slots. For this reason, throughout the paper we do not allow fragmentation.

C. CQI Allocation Framework

In our CQI allocation framework, for each tree level, every MS is associated with a profit function that indicates the "profit of the system" from allocating to this MS a CQI channel corresponding to this tree level. Throughout the paper we

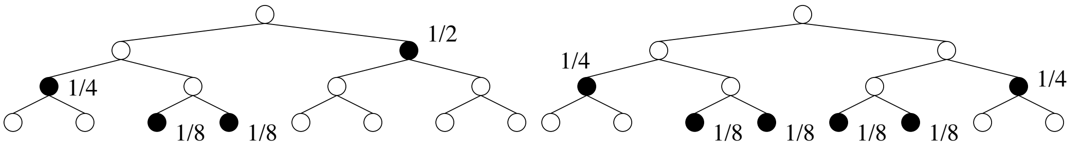

Fig. 2: Examples for two collision-free allocations

frame #	I	I+1	I+2	I+3	I+4	I+5	I+6	I+7	I+8	I+9	I+10	I+11	I+12	I+13	I+14	I+15
	1	2				2				2				2		

Fig. 3: A fragmentation of a CQI channel

concentrate on the following profit function:

$$P_j(l) = \begin{cases} \frac{1}{2^{\left(C - l_j^{\text{MAX}}\right)}} & \text{if } l > l_j^{\text{MAX}} \\ \frac{1}{2^{(C-l)}} & \text{if } l_j^{\text{MIN}} \le l \le l_j^{\text{MAX}} \\ 0 & \text{Otherwise.} \end{cases} \qquad (1)$$

This profit function reflects the inverse relationship between the periodicity and the bandwidth allocated to the CQI channel of an MS and the linear relationship between the bandwidth of the CQI channel and the associated profit. When a tree node in level l is allocated, the corresponding CQI channel has a periodicity of $\tau = 2^{C-l}$. The profit is equal to 0 until the periodicity is small enough. Then, increasing the level of the CQI tree node by 1 doubles the bandwidth and the associated profit. When the level reaches the maximum for that MS, more CQI slots bring no additional profit.

Assumption 1: Let MS$_i$ and MS$_j$ be two MSs. If $l_j^{\text{MIN}} \le l_i^{\text{MIN}}$, then $l_j^{\text{MAX}} \le l_i^{\text{MAX}}$.

We believe that in most systems the value of l_j^{MIN} will be equal for all MSs. For such systems, there is no restriction on the l_j^{MAX} values.

IV. ALGORITHMS FOR CQI ALLOCATION

A. Optimization Criterion

Definition 2: An MS is said to be satisfied if its allocated CQI channel is not smaller than its minimum demand.

Definition 3: Consider 2 CQI allocation vectors a_1 and a_2. The following rules indicate which of the two is better than the other from the BS perspective:

1) If all MSs are satisfied in both a_1 and a_2, then the better allocation is the one whose aggregated profit $\sum_{j=1}^{n} P_j(l_j)$ is larger.
2) If the number of satisfied MSs in a_1 is different from the corresponding number in a_2, then the allocation with the larger number of satisfied MSs is better.
3) If not all the MSs are satisfied and the number of satisfied MSs is equal in both a_1 and a_2 then the assignment that has more free bandwidth than the other is better.
4) Otherwise, the assignment with the larger aggregated profit is better. ■

The rationale behind this definition is that satisfying all active MSs is our primary optimization target. Only if every MS is satisfied, can we take into account the profit. When some MSs are not satisfied, we prefer an assignment that has more free bandwidth because such an assignment is likely to satisfy more MSs in the near future.

B. CQI Allocation When the Tree Is Empty

We start with the basic problem, where we assume that the CQI allocation tree is empty and the goal is to find the best allocation for a given set of MSs. This problem is referred to as CF-CQI-E (Collision Free CQI allocation in an Empty tree) and is formally defined as follows:

Problem 1 (CF-CQI-E):

Instance: The height of the allocation tree C and the profit function P_j for every MS$_j$ $1 \le j \le n$, where n is the number of active MSs.

Objective: Find the best allocation (based on Definition 3).

Algorithm 1: (An optimal algorithm for CF-CQI-E)

1) Sort the MSs in ascending order of their minimum demands. Without loss of generality, suppose that $l_1^{\text{MIN}} \le l_2^{\text{MIN}} \le ... \le l_n^{\text{MIN}}$. Then, find the largest integer k such that $\sum_{i=1}^{k} 2^{\left(l_i^{\text{MIN}} - C\right)} \le 1$.
2) Allocate to each of the first k MSs a CQI channel with the minimum required bandwidth and set $allocated\_bandwidth = \sum_{i=1}^{k} 2^{\left(l_i^{\text{MIN}} - C\right)}$.
3) If $k < n$ (not all MSs have been satisfied), stop and return the allocation of the k CQI channels.
4) Else, sort the l_j^{MAX} values in descending order. Without loss of generality, assume that $l_1^{\text{MAX}} \ge l_2^{\text{MAX}} \ge ... \ge l_n^{\text{MAX}}$. Then, go through the sorted list and try to increase the level of each MS$_i$ from l_i^{MIN} to the largest level $l \le l_i^{\text{MAX}}$ still available in the tree. ■

Note: In step 3 there might be cases where not every MS is satisfied, while there is some bandwidth that can be used for increasing the allocation of satisfied MSs. Nevertheless, following rule 3 of Definition 3, Alg. 1 does not increase the allocation of satisfied MSs in such a case.

Theorem 1: Alg. 1 returns the best CQI allocation.

C. CQI Allocation with No Change to Satisfied MSs

We now define the second problem, referred to as CF-CQI-NC (Collision Free CQI allocation with No Change to satisfied MSs). Here, some bandwidth of a super-channel tree becomes available following the release of a CQI channel. This bandwidth should be allocated by the BS to some unsatisfied MSs.

Problem 2 (CF-CQI-NC):

Instance: The height of the allocation tree C, the profit function P_j for every MS$_j$ $1 \leq j \leq n$ and information about already allocated CQI channels.

Objective: Find the assignment of unused bandwidth that gives the best allocation without changing the status of occupied CQI nodes.

Definition 4:

(a) A free subtree in T is a subtree that contains only free nodes.

(b) A free subtree is max-free if the subtree rooted at its parent is not free.

Algorithm 2: (An optimal algorithm for CF-CQI-NC)

1) Let T be the current allocation tree. Find all of the max-free subtrees in T and sort them in ascending order of their height (bandwidth). Let U be the set of unsatisfied MSs.
2) Sort the MSs in U in ascending order of their l_j^{MIN} values. Check if all these MSs can be satisfied using the max-free subtrees. This can be performed by going over each MS$_j$ in the sorted list and allocating this MS the leftmost node in level l_j^{MIN} of the shortest max-free subtree whose height is not smaller than l_j^{MIN}.
3) If not every MS in U can be satisfied, satisfy the maximum number of MSs and stop.
4) Else (all of the MSs in U can be satisfied), try to increase the allocation of the MSs in U (note: since CF-CQI-NC does not allow changes in the tree, we do not seek to increase the bandwidth allocated to MSs not in U) in the following way:
    a) Sort the MSs in U in descending order of their l_j^{MAX} values. Without loss of generality, assume that $l_1^{\text{MAX}} \geq l_2^{\text{MAX}} \geq .... \geq l_{|U|}^{\text{MAX}}$ holds for these MSs.
    b) Go over the sorted list and for every MS$_j$ find the largest level $l \leq l_j^{\text{MAX}}$ such that (i) there is a free level l subtree and (ii) MS$_{j+1}, ..., MS_{|U|}$ can still be satisfied. ■

Theorem 2: Alg. 2 returns the best CQI allocation without changing the allocation of occupied CQI tree nodes.

D. CQI Allocation with Minimum Number of Changes

The third problem we define is referred to as CF-CQI-MC (Collision Free CQI allocation with Minimum number of Changes). Like Problem 2, this problem is relevant when most of the tree is occupied, but there are some unsatisfied MSs. In contrast to CF-CQI-NC, we allow the BS to make some changes in the tree in order to satisfy as many unsatisfied MSs as possible (a "change" is a satisfied MS whose allocation is modified). The number of such changes is bounded because each change requires the BS to send an extra signaling message. The upper bound is derived from the optimal solution to CF-CQI-E.

Problem 3 (CF-CQI-MC):

Instance: Same as Problem 2.

Objective: Let M be the number of satisfied MSs in the optimal solution of CF-CQI-E. Let m be the minimum number of changes required in order to satisfy M MSs. Find the best allocation that requires no more than m changes.

Theorem 3: CF-CQI-MC is NP-hard.

We propose the following heuristic for CF-CQI-MC. First, the tree nodes are removed one by one in a predetermined order. After each node removal, Alg. 2 is invoked in order to check how many unsatisfied MSs can be allocated a CQI channel with no further change to the tree. The process stops when the number of removed nodes exceeds a certain limit or when the solution returned by Alg. 2 satisfies the maximum number of MSs, which is found using Alg. 1.

Algorithm 3: (Heuristic for CF-CQI-MC)

1) Run Alg. 1 to find the maximum number S of satisfied MSs.
2) If Alg. 2 can satisfy S MSs (with no change to the tree), stop and return this allocation. Else, check all m combinations of removing a single node, where m is the number of allocated tree nodes. If at least one of these combinations satisfies S MSs, stop and return the optimal one.
3) Sort the occupied nodes in the tree in 2 different ways: (i) ascending order of their height; (ii) descending order of their height;
4) For every sorted list from step 3, remove one node at a time and invoke Alg. 2. From all the solutions found, consider the one with minimum number of changes that satisfies S MSs. If this number does not exceed the limit, return it; else, return no solution. ■

V. SIMULATION STUDY

Throughout this section we consider a CQI allocation tree whose height is $C = 8$. We consider 3 possible profit functions: ($l^{\text{MIN}} = 0$, $l^{\text{MAX}} = 3$), ($l^{\text{MIN}} = 4$, $l^{\text{MAX}} = 6$) and ($l^{\text{MIN}} = 5$, $l^{\text{MAX}} = 7$). The normalized load of the CQI super-channel is defined as the total normalized minimum CQI bandwidth of all MSs and is equal to $\sum_{j=1}^{n} 2^{l_j^{\text{MIN}}-C}$.

We use a list of 25 MSs for which the profit function is chosen randomly and we invoke Alg. 1 to allocate CQI channels to these MSs. Then, we simulate $1,000$ random events of joining or leaving MSs. Each sequence of $1,000$ events is repeated 100 times with different seeds and the results

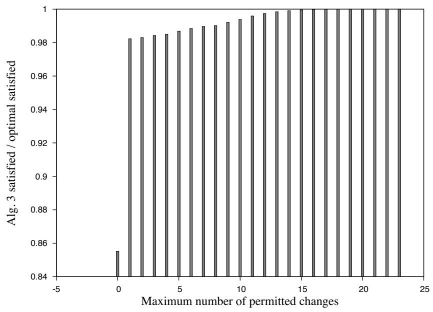

Fig. 4: The number of MSs satisfied by Alg. 3 divided by the maximum number of MSs that can be satisfied by Alg. 1 vs. the maximum number of permitted changes

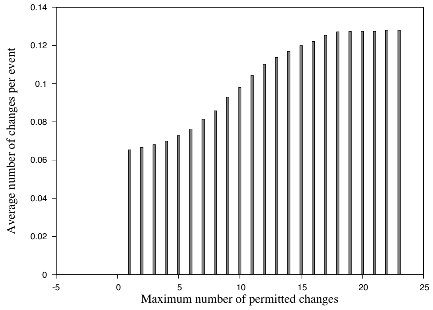

Fig. 5: The average number of changes per event performed by Alg. 3 vs. the maximum number of permitted changes

are averaged. When the event is that an existing MS leaves, we use uniform distribution for selecting a specific MS. These parameters yield a normalized load of ≈ 1.6.

We compare the performance of Alg. 3 with different limits on the number of changes it can make. The results are shown in Fig. 4, where the x-axis indicates the maximum number of changes and the y-axis indicates the fraction of MSs Alg. 3 satisfies compared to the maximum possible number found by Alg. 1. Note that when Alg. 3 is allowed to make no change, its performance is identical to that of Alg. 2. In such a case, Alg. 3 satisfies only 86% of the unsatisfied MSs that can be satisfied by Alg. 1. If Alg. 3 is allowed to make one change, it can satisfy 98% of the requests that can be satisfied by Alg. 1. As Fig. 4 shows, additional changes do not significantly improve this result.

Fig. 5 shows the average number of changes per event. We can see that this number is ≈ 0.065 if the algorithm is allowed to make one change. If Alg. 3 is allowed to make more changes, this number slightly increases. With up to 10 changes, Alg. 3 can satisfy ≈ 0.995 of the requests that can be satisfied by Alg. 1 and the number of changes per event increases to 0.1.

Fig. 6 shows the effect of the normalized load on the performance of Alg. 3 when the maximum number of changes is limited to $1, 5$ and 10. The y-axis is similar to that in Fig. 4, namely, it indicates the number of MSs satisfied by Alg. 3 divided by the maximum number of MSs that can be satisfied as found by Alg. 1.

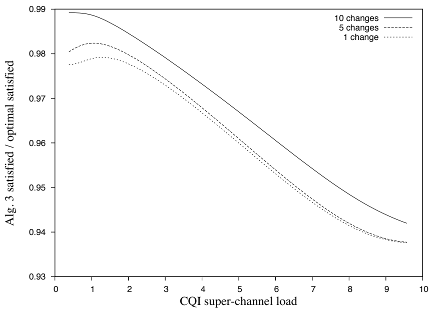

Fig. 6: The number of MSs satisfied by Alg. 3 divided by the maximum number of MSs that can be satisfied by Alg. 1 vs. the CQI super-channel load

We can see that the fraction of satisfied MSs increases until the load reaches ≈ 2, and then it decreases. The reason for that is that when the load is low, Alg. 3 allocates to some MSs more than their minimum demand. Such allocation has negative impact on new MSs, which are less likely to get their minimum demand. When the load increases, Alg. 3 allocates to each MS its minimum demand, and its performance is closer to the optimal performance of Alg. 1. After a certain point (≈ 2), further increase of the load requires the algorithms to ignore nodes whose minimum demand is high. With respect to this requirement, Alg. 1 has more flexibility than Alg. 3 and therefore the relative performance of Alg. 3 decreases.

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