Abstract—Implementation of an efficient CQI feedback mechanism is the focus of the study presented in this paper. OFDMA-based systems such as 3GPP Long Term Evolution (LTE) downlink and WiMax require an accurate CQI feedback to allow effective operation of the adaptive modulation and coding. Besides accuracy, such mechanism should impose only a low overhead when using uplink resources for conveying the CQI information. Unlike the Best-M CQI feedback algorithms where only the M highest CQI's and their locations are reported, a full-band feedback method compresses the whole CQI vector and transmits the compressed vector in the uplink channel. In this paper, application of the Haar transform for a full-band CQI report is investigated and its performance is compared against DCT-based compression schemes. Full-band Haar CQI feedback offers a flexible process for CQI feedback that can be easily adapted to different operating scenarios. Key features of Haar compression are incremental update and very low complexity for compression and decompression. Simulation results indicate that the full-band Haar scheme achieves significantly higher throughput than the DCT-based schemes at low speeds and about the same performance at higher speeds.

Index Terms—Haar, CQI, feedback, frequency selective scheduling.

I. INTRODUCTION

Frequency selective scheduling is an attractive feature in OFDMA-based systems such as LTE downlink and WiMax. It allows optimum usage of the allocated spectrum by assigning proper modulation and coding to each user according to their channel conditions. In order to support frequency selective scheduling in the downlink, the mobile user needs to feedback channel quality indication (CQI) of the downlink channel to the base station.

In OFDMA systems, the unit used for frequency selective scheduling is a sub-band, which includes a number of consecutive subcarriers. To fully support the frequency selective scheduling, ideally each mobile user needs to feedback a set of CQI values, one for each sub-band. However, this will lead to overwhelmingly large CQI feedback overhead.

The challenge of designing low overhead CQI feedback schemes has spurred many research initiatives in recent years. A summary of the state of the art in academia can be found in [1]. Also, numerous CQI feedback and compression schemes have been proposed with different levels of compression and system performance [2]-[4] for LTE.

In general, most of the proposed CQI feedback schemes fall under either full-band or Best-M categories [2]-[4]. In full-band schemes, the CQI information of all the sub-bands in the entire cell bandwidth is compressed and then the compressed CQI information is reported to the base station. An example of the schemes in this category is DCT significant-M feedback [4]. The second category includes techniques that are based on feedback of only a limited number of the highest CQIs among all sub-bands, such as Best-M individual, DCT-partitioning. The effectiveness of these methods varies and each has its own inherent trade-off in terms of performance and feedback overhead [2]-[4], [7]-[9].

In [7], application of Haar compression in Best-M CQI feedback was investigated. In this paper, we investigate the application of the Haar transformation to full-band CQI feedback and we compare its performance against DCT-based compression schemes. Full-band Haar CQI feedback offers a flexible process for CQI feedback that can be easily adapted to different operating conditions. Important features of Haar are incremental update and very low complexity for compression and decompression.

The rest of the paper is organized as follows: At first in Section II, the 3GPP LTE system is briefly described. Then, a review of Haar compression and its applications for full-band CQI feedback are provided in Sections III and IV, respectively. In section V, the throughput performance and the feedback overhead requirement of the proposed approach are compared against other compression based CQI feedback schemes. Final conclusion and remarks are provided in Section VI.

II. SYSTEM DESCRIPTION

In this section, we present the Full-band CQI feedback and Haar compression in the context of a general OFDMA system. Without any loss of generality, for a better presentation of its impact in a real system, the downlink of the LTE system is considered. The time in the 3GPP LTE system is divided into radio frames [5]-[6]. Each radio frame (10 ms) is divided into 10 sub-frames of 1 ms each. A sub-frame is the minimum time unit for transmission in both
uplink and downlink. Therefore, a sub-frame is also called a transmission time interval (TTI).

The basic concept of frequency selective scheduling in the 3GPP LTE systems is depicted in Figure 1. Each handset needs to estimate the channel quality and report the CQI of downlink sub-bands to the base station. The network schedules and allocates sub-bands for mobile users based on the reported CQI. Then, the modulation and coding set (MCS) of each scheduled user is adapted according to the reported CQI.

The first element of the vector, in **Bold**, is called “Approximate” and the remaining elements are called “Detail” coefficients.

In an abstract form, the successive averaging and differencing steps can be mathematically expressed by a compression matrix $W_8^i$. For example, for a vector with a length of 8,

$$y_3 = \begin{bmatrix} y_3(8) & y_3(7) & \cdots & y_3(1) \end{bmatrix} = yW_8$$

where

$$W_8 = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & 0 & \frac{1}{2} & 0 & 0 & 0 & 0 \\ \frac{1}{2} & \frac{1}{2} & 0 & \frac{1}{2} & 0 & 0 & 0 & 0 \\ \frac{1}{2} & \frac{1}{2} & 0 & 0 & \frac{1}{2} & 0 & 0 & 0 \\ \frac{1}{2} & \frac{1}{2} & 0 & 0 & \frac{1}{2} & 0 & 0 & 0 \\ \frac{1}{2} & 0 & \frac{1}{4} & 0 & \frac{1}{2} & 0 & 0 & 0 \\ \frac{1}{2} & 0 & \frac{1}{4} & 0 & \frac{1}{2} & 0 & 0 & 0 \\ \frac{1}{2} & 0 & -\frac{1}{4} & 0 & 0 & \frac{1}{2} & 0 & 0 \\ \frac{1}{2} & 0 & -\frac{1}{4} & 0 & 0 & 0 & \frac{1}{2} & 0 \end{bmatrix}$$

As such, the decompression can be easily implemented by

$$y = y_3F_8^i,$$

where

$$F_8^i = W_8^{-1} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & -1 & -1 & -1 & -1 & -1 \\ 1 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & -1 & -1 & -1 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & -1 \end{bmatrix}$$

### III. HAAR COMPRESSION

Haar compression is based on the Haar wavelet transform. A detailed description of the Haar compression method can be found in [10]-[11]. Haar compression encodes an input stream in multiple steps according to the level of detail of the input sequence. It belongs to the class of lossy compression methods, and is recognized as an effective and low complexity compression/decompression means for processing 1- or 2-dimensional data.

The main idea of using the Haar transform to compress a data vector is to shift the weight and importance of the vector elements to the first element of the vector.

Assuming a vector with 2^k elements, the transformation consumes i steps of sum and difference operations [10]-[11]. The elements of the vector are grouped in groups of 2, and then the sum and the difference terms for each group are computed and the results are divided by two. In the following steps, the same procedure is applied only on the first half of the compressed vector and the second half is left untouched. Hence, the process continues in i consequent steps resulting a compressed vector,

$$y_i = \begin{bmatrix} y_{i1} & y_{i2} & y_{i3} & y_{i4} & \cdots & y_{i(2^i-1)} & y_{i2^i} \end{bmatrix}$$

The first element of the vector, in **Bold**, is called “Approximate” and the remaining elements are called “Detail” coefficients.

The general mechanism for uplink CQI feedback can be summarized as follows: The handset performs several measurements, computes CQI values and performs compression on the whole CQI vector. According to the channel condition, handset mobility and the CQI feedback granularity requested by the network, the handset sends all or some of the elements of the compressed vector. At the network, the received vector is decompressed using always the same matrix F. Hence, the total number of bits transmitted is:

$$N_{total} = \sum_{i=1}^{N_c} b_i$$

where $N_c$ and $b_i$ are the number of elements of the compressed vector sent and the number of bits per compressed vector element, respectively.

The size of the compression/decompression matrices is determined from the number of $N_{total}$ sub-bands. For a system with $N_b=25$ sub-bands, the size of the compression/decompression matrices will be 32×32. The remaining 7 unused places in the input vector are filled by zeros. The locations of the zeros are arbitrary, however it is more reasonable to spread them across the vector to balance the weight of the vector. Hence, the following locations in the input CQI vector are filled with zeros.

$$y(6) = 0, y(10) = 0, y(14) = 0,$$

$$y(18) = 0, y(22) = 0, y(26) = 0, y(28) = 0$$

It should be noted that the zero insertion does not increase the overhead. After the compression the following 7
elements are dropped as they are not relevant in decompressing the compressed vector. Let $y_i$ be the compressed vector, then the elements $y_5(19), y_5(21), y_5(23), y_5(25), y_5(27), y_5(29), y_5(30)$ (8) can be dropped without any loss of information. This can be simply explained by noting that the decompression mechanism is aware of the locations of the inserted zeros as stated in Equation (7). Therefore, they have no effect on sum and difference terms, and can be ignored for decompression without any penalty [11].

Assuming 5 bits per CQI value, the first element of the compressed vector that is equal to the mean of the vector expects 5 bits of resolution. However, the remaining elements that are basically differential information can be represented by 4 bits. Thus,

If $N_c = 4$ coefficients $\Rightarrow N_{Total} = 5 + 3 \times 4 = 17$ bits
If $N_c = 8$ coefficients $\Rightarrow N_{Total} = 5 + 7 \times 4 = 33$ bits

Therefore for $N_c = 8$ and assuming a Reporting Interval (RI) of 4 TTIs, the average CQI budget will be,

$$\frac{33}{4} = 8.25 \text{ bits/TTI}$$

Coefficient bits can be reduced or expanded to result in an integer number of bits per message, alternatively rate-matching can be used.

Figure 2 shows incremental update of the full-band Haar compression/decompression process. As shown, decompression with two coefficients yields only information about the average of the lower and upper bands. However, by transmitting more coefficients, a higher accuracy in the reconstruction of the original CQI vector is attained.

A. Main Features

There are several benefits using the proposed full-band Haar CQI. Compared to Best-M methods [2], there is a significant saving in feedback overhead by not requiring sending the label and average information.

Gradual update is possible. In other words, it is not necessary to receive the whole set of coefficients at the network to start updating the scheduler. The network can update the scheduler per reception of each element. Thus, the update rate could be every TTI.

By using incremental update, the system can be easily adapted to various channel, mobility conditions and/or a given CQI budget.

In comparison against other full-band compression methods, full-band Haar is significantly less complex. For a given dimension, Haar (de)compression matrices need a significantly smaller number of computations. The matrix calculations rely only on basic shift and addition/subtraction operations. Also it is important to note that a significant number of matrix elements are zero resulting in more savings in computations. For example, for vector lengths of 4, 8, 16 and 32, the number of elements of the compression/decompression matrices that are zero are ¼, ½, ¾ and 192/1024, respectively.
B. Updating Strategies

For a given update interval, two strategies might be considered for CQI feedback using full-band Haar compression, namely: One-shot and Incremental. Assuming an update rate of 4 TTI, here are the steps taken in one-shot update:

1. Handset takes a snapshot once every 4 TTIs.
2. In every TTI, handset sends \( \frac{1}{4} N_{\text{total}} \) bits available from the step-1.
3. Upon complete reception of \( N_{\text{total}} \) bits, the network decompresses the receive vector.

The steps for the incremental update can be summarized as follows:

1. Take a snapshot once every TTI,
2. In every \( i_{\text{th}} \) TTI, send the \( \frac{1}{4} N_{\text{total}} \) bits of the total \( N_{\text{total}} \) bits,
3. Upon receiving each \( \frac{1}{4} N_{\text{total}} \) bits, the network updates only that portion of the \( N_{\text{total}} \) and then decompresses the available partially updated vector.

\[ \text{Figure 3 – a) One-shot update, b) Incremental update} \]

V. PERFORMANCE RESULTS

A. Simulation Methodology and Parameters

A system-level simulation using a proportional fair scheduler was performed to evaluate the performance of the Haar-based full-band CQI feedback against similar competitive schemes in a 10 MHz system. In the downlink transmission RB grouping is assumed, where one CQI sub-band contains 2 RBs. In the simulation a CQI granularity of 20 MCS levels is used. The impact of CQI measurement delay and errors are considered as suggested in [3] and [9]. The simulation parameters are listed in Table 1.

B. Simulation Results

The average sector throughput performance of full-band Haar, DCT Significant-M [4] and DCT Partitioning [4] is evaluated under different CQI feedback intervals. The update mechanism for decompression is based on the incremental approach. Figures 4 and 5 show the average sector throughput performance of the system for handset speeds of 3 km/h and 15 km/h, respectively.

For each case, there are three curves for the full-band Haar, each corresponding to a particular feedback interval (RI). Each feedback interval also implies the number of the coefficients sent to the network for decompression. As demonstrated in both figures, increasing RI from 2 to 8 ms improves the performance. The fundamental reason for this behavior is that by extending the RI, the network receives a higher number of coefficients and therefore will be able to decompress the CQI information with more accuracy (see figure 2).

Since the uplink control channel for CQI feedback is designed to support about 10 information bits per TTI, the reference point of interest for the CQI budget in this paper is assumed 10 bits/TTI. It is worthwhile to note that at handset speed of 3 km/h, the full-band Haar scheme offers significantly better performance than other schemes over a wide range of bits/TTI. At speed of 15 km/h, the full-band Haar with RI=4 and RI=8 performs about the same as the DCT schemes at 10 bits/TTI. For RI=4 and RI=8, it is important to mention that such performance is achieved by requiring only 8.25 and 8.125 bits/TTI that is 10% less than the assumed budget. This could result in higher coding gain to improve cell edge performance.

At higher mobile user speed, e.g. 15 km/h, the average sector throughput decreases remarkably. This is because the CQI feedback intervals of interest (4, 6, 8 and 10 TTIs) are comparable to the channel coherence time, which means that the multipath channel fluctuates during the feedback interval. Hence, large feedback intervals introduce inaccuracy to the reported CQI and corresponding base station’s scheduling, which in turns degrades the average sector throughput.

### Table 1 – Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular Layout</td>
<td>Hexagonal grid, 19 cell sites, 3 sectors per site</td>
</tr>
<tr>
<td>Inter-site distance (ISD)</td>
<td>500 m</td>
</tr>
<tr>
<td>Number of Tx antennas at network</td>
<td>1</td>
</tr>
<tr>
<td>Number of receive antennas</td>
<td>2</td>
</tr>
<tr>
<td>Distance-dependent path loss</td>
<td>( L=1 + 37.6 \log(R), ) R in kilometers ( l=128.1 - 2 \text{GHz} )</td>
</tr>
<tr>
<td>Lognormal Shadowing</td>
<td>Similar to UMTS 30.03, B1.41.4</td>
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<tr>
<td>Shadowing standard deviation</td>
<td>8 dB</td>
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<tr>
<td>Penetration Loss</td>
<td>20 dB</td>
</tr>
<tr>
<td>Channel model</td>
<td>Typical Urban (TU)</td>
</tr>
<tr>
<td>Antenna pattern (horizontal)</td>
<td></td>
</tr>
<tr>
<td>(For 3-sec. cell sites with fixed ant. patterns)</td>
<td>( A(\theta) = \min \left[ \frac{1}{12}, \frac{1}{\theta_{\text{db}}}^2, A_{\text{a}} \right] )</td>
</tr>
<tr>
<td>( \theta_{\text{db}} = 70 ) degrees, ( A_{\text{a}} = 20 ) dB</td>
<td></td>
</tr>
<tr>
<td>BS Antenna Gain plus cable loss</td>
<td>15 dB</td>
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<tr>
<td>Carrier Frequency</td>
<td>2.0 GHz</td>
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<tr>
<td>System Bandwidth</td>
<td>10 MHz</td>
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<tr>
<td>RB bandwidth</td>
<td>180 KHz</td>
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<tr>
<td>Number of mobile users per Sector</td>
<td>10</td>
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<tr>
<td>Mobile user speeds of interest</td>
<td>3 km/h, 15 km/h</td>
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<tr>
<td>Maximum Node B transmission power</td>
<td>35 dBm</td>
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<td>Mobile user Traffic Model</td>
<td>Full Buffer</td>
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<td>Noise Figure</td>
<td>90 dB</td>
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<tr>
<td>Thermal noise density</td>
<td>-174 dB/Hz</td>
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<tr>
<td>Scheduler</td>
<td>Proportional Fair</td>
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<td>HARQ</td>
<td>Asynchronous (Chase combining)</td>
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<td>CQI measurement error</td>
<td>Gaussian zero-mean error model</td>
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<td>CQI averaging window</td>
<td>4 TTIs</td>
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<tr>
<td>CQI feedback delay</td>
<td>2 TTIs</td>
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<tr>
<td>CQI feedback interval (RI)</td>
<td>2, 4, 6 and 8 TTIs</td>
</tr>
<tr>
<td>Target BLER</td>
<td>10%</td>
</tr>
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</table>
VI. CONCLUSIONS AND DISCUSSIONS

In this paper, we propose the application of Haar compression to full-band CQI feedback for OFDMA based systems. Full-band Haar CQI feedback offers a flexible mechanism for CQI feedback that can be easily adapted to different operating scenarios. Key features are incremental update and very low complexity for compression and decompression. Simulation results show that under the constraint of a low overhead budget per TTI, i.e., ~10 bits/TTI, the full-band Haar scheme achieves significantly higher performance than the DCT schemes at a low speed of 3 km/h and about the same performance at a higher speed of 15 km/h. The above mentioned performance for RI=4 and RI=8 are achieved at CQI budgets of only 8.25 and 8.125 bits/TTI that are 10% less than the initially assumed 10 bits/TTI budget.

ACKNOWLEDGMENT

The authors would like to thank Donald Grieco, Robert Olesen and Joseph Levy for their valuable feedback during the course of this work.

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