Comparing Uplink Schedulers for LTE

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ABSTRACT

The choice of SC-FDMA for uplink access in Long Term Evolution (LTE) facilitates great flexibility in allocating medium resources to users while adapting to medium condition. A multicarrier multiple access technique, SC-FDMA gains an advantage over OFDMA in that it reduces the energy requirements in user equipment. 3GPP Releases 8 and 9, however, do not detail a specific scheduler and, accordingly, proposals have been made in the literature in designing an efficient and capable uplink scheduler for LTE. This paper presents a preliminary performance evaluation for representative proposals, and offers medium of comparison in order to highlight the individual characteristics of each proposals.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: wireless communication; C.2.3 [**Computer-Communication Networks**]: Network Operations—*Network management*

General Terms

Performance, Experimentation

Keywords

Uplink scheduling; SC-FDMA; Long Term Evolution

1. INTRODUCTION

Based on 3GPP's Release 8, Single Carrier-FDMA (SC-FDMA) is the multiple access technique for LTE's uplink [1]. This choice facilitates achieving high data rates (up to 50 Mbps) and reducing the battery requirements in User Equipment (UE) given SC-FDMA's low peak-to-average-power ratio (PAPR). SC-FDMA is based on a DFT-spread of OFDM symbols, and is thus additionally characterized by having lower power path mitigation and simpler frequency domain equilization than OFDMA — the multiple access technique chosen in WiMax. With the viability of Channel-Dependent-Scheduling (CDS), SC-FDMA further allows to improve both the network performance and the mobile user experience in data delivery.

Among many architectural improvements, 3GPP Release 8 specified that scheduling the uplink channel would take place at the base station, or eNodeB, to enhance the system's response. The standard, however, does not mandate a specific scheduler. Accordingly, several proposals have been made in the literature, including [2], [3], [4], for schedulers that best utilize the available resources in order to increase the networks' performance in terms of bandwidth utilization and data throughput.

The objective of this paper is to compare representative proposals from the literature in terms of their fairness, spectral efficiency and throughput. We limited our scope to proposals that are fully LTE-compliant, and set unified settings in order to offer a fair comparison. As with other scheduling schemes, we find that there is a definite trade-off between achieving fairness in user allocation and maximizing throughpout. The constraint of contiguous allocations, mandated by the standard, does have a definite effect on scheduling design. Notwithstanding, we distinguish that reasonable performance can be achieved without sacrificing complexity.

2. OVERVIEW OF SCHEDULING IN LTE

2.1 Resource Allocation in SC-FDMA

Mapping subcarriers to different users is performaed in chuncks called Resource Blocks (RB). Each RB in LTE has a time duration of 0.5 ms and contains 12 subcarriers that span a bandwidth of 180 kHz. Depending on the network's cyclic prefix, i.e. normal or extended, each RB respectively contains 7 or 6 symbols. Two consecutive RBs make up a 1 ms subframe subframe [3], [5].

The subcarrier-mapping resolves which user can transmit on which group of RBs. There are two methods that an SC-FDMA uplink scheduler can use to assign subcarriers: distributed FDMA (DFDMA) and localized FDMA (LFDMA) [2], [5]. In DFDMA, RBs assigned to a certain user are equally spaced across the entire bandwidth. Localized subcarrier mapping (LFDMA), on the other hand , refers to allocating subcarriers to each user in the network in a contiguous manner. While DFDMA outperforms LFDMA in terms of frequency diversity, the latter achieves better user diversity as the allocation for a certain users undergo comparable channel quality [6]. Figure 1 illustrates the difference between Distributed and Localized FDMA allocation schemes.

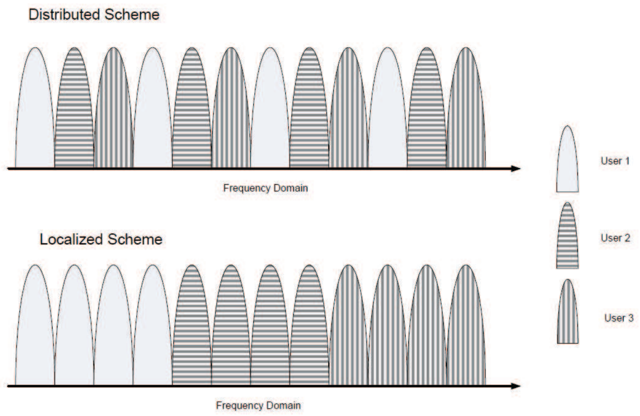

Figure 1: Distributed vs. Localized FDMA allocation schemes.

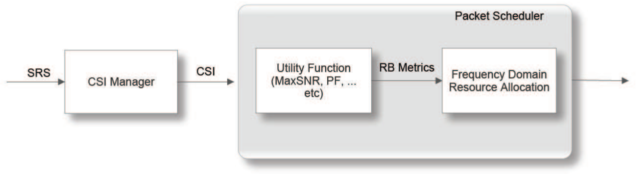

Figure 2: Scheduler Workflow.

2.2 Channel-Dependent Scheduling

Channel-dependent scheduling (CDS) can efficiently utilize the available bandwidth by assigning RBs to UEs over which such UEs have advantageous channel conditions [2].

Figure 2 demonstrates a general framework followed by the scheduling schemes investigated in our study. 3GPP Releases 8 and 9 specify that scheduling is performed at eNodeB, which constantly monitors the channel conditions for each UE over the entire bandwidth. An eNodeB utilizes channel sounding where each UE sends Sounding Reference Signal (SRS) that spans the entire bandwidth to its serving eNodeB [1]. The eNodeB then extracts channel state information (CSI) and passes it on to the utility-based function block scheduler. The utility function generates a metric value for each RB for each UE, and is derived such that it compromises between the spectral efficiency of data transmission and fairness among all UEs. Once the scheduling metrics are generated, they are passed on the resource allocation block to multiplex UEs along the RB resources. The resource allocation algorithm ensures that each RB is allocated to no more than 1 UE, and that all RBs allocated to a single UE are contiguous along the frequency domain. It is important to note that, due to the dynamic nature of the channels' varying states for each UE, a scheduling assignment is only valid for a specific time period called the Transmission Time Interval (TTI). A CDS scheduler hence needs to perform its scheduling decision once every TTI, where the TTI's duration can be as short as 1 ms.

3. UPLINK SCHEDULING ALGORITHMS UNDER STUDY

In each of the scheduling algorithms studied herein, the scheduler uses a generated metric value for each UE and for each RB. The calculated metrics are arranged into a matrix M, shown in Table 1, of dimensions NxN_{RB}, where N represents the number of UEs in the network, and N_{RB} is the total number of RBs.

UEs	RB_1	RB_2	$\cdots$	$RB_{N_{RB}}$
UE_1	$M_{1,1}$	$M_{1,2}$	$\cdots$	$M_{1,N_{RB}}$
UE_2	$M_{2,1}$	$M_{2,2}$	$\cdots$	$M_{2,N_{RB}}$
$\vdots$	$\ldots$			$\ldots$
UE_N	$M_{N,1}$	$M_{N,2}$	$\cdots$	$M_{N,N_{RB}}$

Table 1: The UEs channel quality for each RB.

In the following we summarize the studied algorithms, namely the First Maximum Expansion (FME), Recursive Maximum Expansion (RME), Minimium Area Difference (MAD) and Search-Tree Based Packet Scheduling (STBPS). We also describe a modification version of FME, called Modified FME (MFME), that we propose to enhance its performance without a substantial increase in complexity. Note that in the evaluation we compare the performance of these algorithm to a basic, channel-independent round robin scheduler.

3.1 First Maximum Expansion

The main principle in FME is to assign RB resources starting from the RB with the highest metric in matrix M, and expand on it. The expansion of the resource assignment for a selected UE on both the right and the left sides of the RB with the largest metric. As the algorithm traverse through each RB, it checks its maximum metric and determines whether the maximum metric still belongs to the UE for which resource are currently being assigned, or whether the maximum metric belongs to another UE. Assigning the RB to the other UE would break the continuity constraints. If both conditions are true, the RB gets assigned to the selected UE; otherwise, the UE is considered *served*, and the currently selected RB is assigned to a new RB. The scheduler then reiterates the expansion procedure.

The complexity of FME is estimated in [2] to be $O(N \cdot N_{RB})$. This estimate is based on the number of searching operations performed on elements in matrix M shown in Table 1 at each step of the algorithm.

3.2 Recursive Maximum Expansion

RME algorithm applies a principle similar to that of FME. However, the main difference between the two algorithms is the action taken when reaching a RB whose maximum metric belongs to a UE other than the one for which RBs are assigned. When this happens, RME considers the previous UE as served, and removes it from the list of UEs for which resources are yet to be assigned. The algorithm then performs a recursive search of the maximum metric onthe remaining RBs. In case all UEs become served while some RBs are still unallocated, the algorithm checks the UEs to which neighboring RBs are already assigned, and distributes the remaining RBs among these UEs to ensure contiguity of RB resource allocation.

According to [2], RME is similar to FME in terms of the complexity of the search operations performed, and hence exhibits a computational complexity of $O(N \cdot N_{RB})$

3.3 Minimum Area Difference

The MAD algorithm allocates resources to different UEs such that it provides the minimum difference between the cumulative metrics of different users and the envelope-metric [2]. The envelope metric represents the envelope of all the users metrics (i.e. the maximum metric value for any given RB). When scheduling resources to different UEs, MAD works at the resource chunks (RCs) rather than with RBs. RC is defined as the region of contiguous RBs over which the maximum metric values belong to a single UE. Working with RCs is established by converting the M matrix inputted to the algorithm into another matrix (M) with dimensions NxN_{RC}, where N_{RC} is the number of RCs, and the metric values in the new M are defined as the area difference between the envelope-metric and the metric of a given UE. MAD algorithm performs a modified version of a breadth-first search algorithm to the combinations of different RCs in matrix M to minimize the summation of the area difference values in M. Working with RCs rather than RBs significantly reduces the computational complexity of the MAD algorithm. However, the performance gain here is dependent on the number of different resource chunks. In the worst case scenario, the computational complexity of the MAD algorithm can be in the order of $O(N_{RC}^{N-1})$.

3.4 Search-Tree Based Packet Scheduling

Except for MAD, the algorithms described above are examples of CDS algorithms that aim to assign each RB to a UE that best utilizes the bandwidth occupied by that RB in a contiguous fashion. The STBPS, however, employs a binary-search tree to allocate uplink resources to UEs to *globally* maximize the overall utilization of the uplink bandwidth [4]. STBPS assigns an RB to a certain UE such that to maximize the global metric, which is the sum of the all the metrics of the assigned UE-RB pairs. Once the search is performed, the algorithm chooses the search-tree path with the highest sum of metrics. Hence, similar to MAD, an RB or a group of contiguous RBs are not necessarily assigned to the UE that achieve the highest metrics.

3.5 Modified FME

We propose a modification to the part where FME expands on the allocation for a certain UE on both sides. In FME, the algorithm checks the columns of matrix M one-by-one to find the maximum value in each column, then assigns that RB to the same previous UE either if it has the maximum value or if the maximum value belongs to another, already scheduled UE (idle UE) [2]. The algorithm, therefore, stops searching for another maximum if the first maximum was for an idle user, and allocates this RB to the current user even if it does not have the next maximum channel quality for this RB. MFME modifies this expansion step continuing the search between the non-idle UEs to allocate this RB to the UE with the next maximum channel quality, whether or not it is the current UE. As the algorithm checks martix M column-wise, it checks if the previous UE does not have the highest metric on the RBs to be expanded on. If so, the algorithm checks for the next globally highest metric for the next-to-be-assigned RB between the non-idle users to not violate the contiguity property of the uplink transmission.

Locating the first maximum requires (NXN_{RB}) comparisons while the second search performed for each of the remaining column requires $(N-1)X(N_{RB})$ comparisons. If a successive search is needed to locate the next non-idle user with the maximum channel quality value, this would require $(N_{RB}-1)$ comparisons . The complexity of MFME is hence $O(N \cdot N_{RB}^2)$ in comparison to FME's $O(N \cdot N_{RB})$.

Parameter	Value
System bandwidth	5 MHz
Sampling rate	15 MHz
Data modulation format	QPSK
Cyclic prefix	20 samples
Transmitter IFFT size	512
Equalization	MMSE
Number of iterations	10^4

Table 2: Simulation parameters.

4. EVALUATION SETUP

4.1 Configuration Parameters

The performance evaluation of the scheduling algorithms under study were executed within a single-cell environment assuming no inter-cell interference. A single BS is simultaneously communicating with a number of UEs that are randomly distributed within the cell coverage. The simulation parameters chosen for the network simulation are summarized in Table 2 below. Each UE within the cell is to have its own channel conditions, and the BS is assumed to have perfect knowledge about channel conditions. The path loss for each UE is modeled using the TU6 path loss model represented in (1) [7]. The simulation environment assumes an FDD transmission where the uplink transmission bandwidth is as listed in Table 2.

$$L_{loss,i,dB} = 128.1 + 37.6 log_{10} d_i + \xi_i \tag{1}$$

where the $L_{loss,k,dB}$ represents the path loss for user i in dB, d_i is the distance between the user i and BS in km, and ξ_i is a shadowing parameter modeled by a normal distribution random variable with standard deviation of 8 dB. In addition, we use the TU6 multipath propagation model which consider a typical urban area with six propagation paths.

$$v(n) = A \cdot \sqrt{P_{rel}(\tau_l)} \cdot w(\tau_l) \tag{2}$$

In (2), $v(n)$ is the discrete time channel impulse response model, A is a normalization parameter used so that the average power $\mathrm{E}\big[\sum |v(n)|^2\big] = 1$ watt, $P_{rel}(\tau_l)$ is the relative power for path l, τ_l is the propagation delay at path l and $w(\tau_l)$ represents zero-mean complex Gaussian noise process at path l. The simulation setup further assumes that users always have full buffers. Hence, the network is to operate at full capacity for the entire simulated time.

4.2 Evaluation Criteria

The scheduling algorithms examined here are evaluated based on three performance metrics, namely fairness, spectral efficiency and aggregated throughput.

A cell's upper spectral efficiency indicates how efficiently the system can utilize the available bandwidth in transmitting error-free data. The analysis of the upper spectral efficiency is derived from Shannon formula shown in (3) [3]:

$$C_i = B_{SC} \times N_i \times log_2(1 + \gamma_i)b/s \tag{3}$$

where C_i represents the spectral efficiency of user i, B_{SC} is the bandwidth of each subcarrier, N_i is the number of subcarriers assigned to user i, and γ_i is the SNR experienced by user i. To compute γ_i for user i:

$$\gamma_i = \left(\frac{1}{\frac{1}{N_i} \sum_{k=1}^{N_i} \frac{\gamma_{i,k}}{\gamma_{i,k} + 1}} - 1 \right)^{-1} \tag{4}$$

where $\gamma_{i,k}$ is the SNR at subcarrier k for user i. Hence, for determining γ_i in (4), we first compute the SNR for each subcarrier k of user i, $\gamma_{i,k}$, as follows:

$$\gamma_{i,k} = \frac{(P_i/N_i).H_{i,k}}{\sigma_k^2} \tag{5}$$

where P_i is the total transmitted power for user i, $H_{i,k}$ is the channel gain for subcarrier k assigned to user i, and σ_k^2 is the noise power of subcarrier k. In turn, the channel gain, $H_{i,k}$, in (5), is determined by (6). The term $V_i(k)$ in (6) is the discrete frequency response, sampled with T_s sampling period of the discrete time impulse response model of the multi-path fading channel for user i, $v_i(l)$, where $v_i(l)$ is defined in (2) [8] and τ_l is the propagation delay at path l.

$$H_{i,k} = \frac{|V_i(k)|^2}{L_{loss,i}} \tag{6}$$

where,

$$V_i(k) = \sum_{l=1}^{L} v_i(l) \cdot \exp\left(-j\frac{2\pi\tau_l}{T_s}\right) \tag{7}$$

The aggregated throughput is the total amount of data successfully received by the eNodeB divided by the entire simulation time.

The third criterion is the fairness of the scheduling algorithm in allocating resources to network users. A fair scheduling algorithm is the one that maximizes the following figure of merit:

$$C_{fair} = \sum_{i=1}^{K} logC_i \tag{8}$$

5. RESULTS

Figure 3 demonstrates the results in terms of data rate fairness as a function of the number of users in the cell. RR has been included in the comparison as a reference for evaluating the five algorithms under study. RR shows a more *ideal* performance in terms of data rate fairness, as it equally allocates RBs to users while respecting the contiguity rule of SC-FDMA scheduling, with no consideration for the channel conditions. All algorithms in Figure 3 show a decaying increase as the number of of UEs increase in the cell. Such behavior is to be expected as the increase of the number of users raises competitiveness on the available resources in the network. Hence, more users transmitting on the uplink means higher chance that the uplink scheduler might skip some users in scheduling sessions. Hence all the simulated algorithms except the RR may cause the UEs with bad channel conditions to wait longer to transmit their data.

Figure 3 also shows the ability of search-tree based scheduler to provide higher fairness level compared to other algorithms, which shows the effectiveness of using a search-tree based algorithms of maximizing fairness at the system level compared to other methods of resource allocation. The search-tree based scheduler, however, does not exhibit the same relative performance level when it comes to the upper-bound spectral efficiency, as shown in Figure 4.

Figure 4 shows the effect of multiuser diversity in the case of the five CDS algorithms on increasing the spectral efficiency with the number of user increase, as well as the performance improvement with respect to the reference RR algorithms. MFME shows up to 4% improvement in spectral efficiency compared to FME when 25 users are present. Also, in terms of relative spectral efficiency, RME and MAD algorithms show strong similarity in terms of performance, with both of them outperforming the other algorithms. Based on such results, an operator might prefer RME over MAD algorithm, since RME can achieve similar performance with less complexity.

Figure 5 shows similar trends in terms of CDS algorithms' performance to that of Figure 4. Both RME and MAD still exhibit relatively similar performance levels, which surpass the performance of other algorithms. Also, FME, MFME, and the search-tree based algorithms have their throughput levels almost coinciding while the number of users in the system is 15 or less, after which both FME and MFME show a noticeable improvement with respect to the search-tree based algorithm. Nevertheless, search-tree based scheduler seems to lag behind others because the use of binary tree to preserve lower computational complexity [4].

Figures 3 through 5 give us a good picture of the performance improvement of modifying the search operations of FME algorithm. MFME shows a noticeable improvement in spectral efficiency and aggregated system throughput when compared to FME. This improvement is achieved as MFME, when changing the resource allocation from one UE to another, it provides more chances for other UEs that might not have been assigned any resources yet. Hence, MFME achieves better multiuser diversity than FME, and consequently better spectral efficiency and throughput. On the other hand, one should not expect MFME algorithm to provide much fairness among users as it still prefers users with good channel conditions. As Figure 3 illustrates, MFME provides no significant increase in fairness relative to FME.

6. CONCLUSIONS

In this paper, we evaluated the performance of representative schedulers proposed for LTE uplink. The studied proposals exhibited comparable performance, despite their varying complexity. We also investigated a suggested modification on one of the proposals, namely First Maximum Expansion. The modification displayed a reasonable increase in performance in terms of spectral efficiency and aggregated throughput. We observe, however, that the Residual Maximum Expansion, proposed by [2], exhibited a comparable performance while having the least complexity. Such behavior is promising as it indicates that acceptable performance can be achieved at low processing requirements. Our intent for future work is to expand on this evaluation to include inter-cell interference, mobility and a varying traffic load.

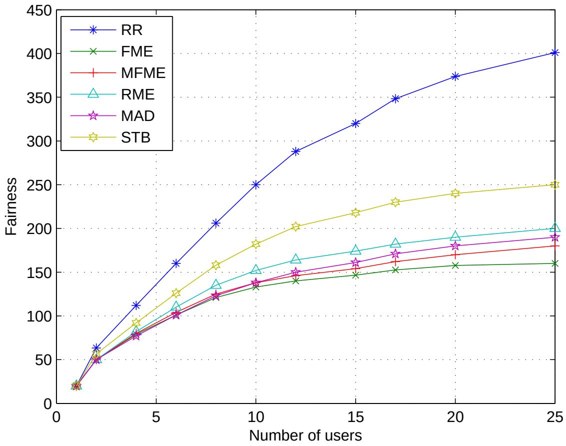

Figure 3: Algorithm fairness vs. number of users

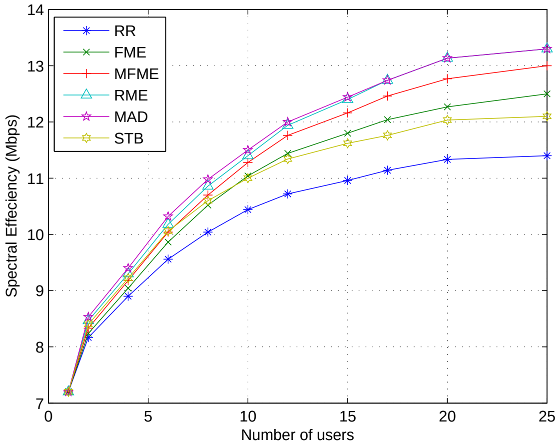

Figure 4: Upper spectral efficiency vs. number of users

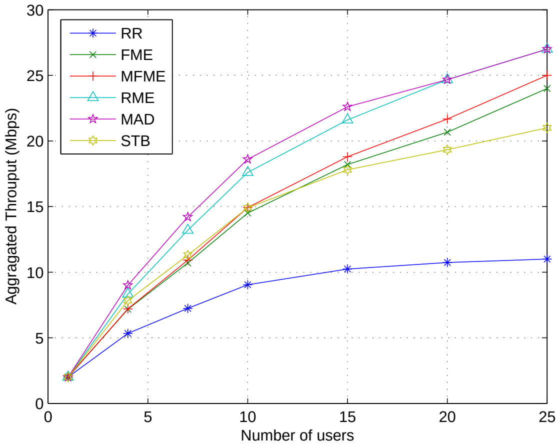

Figure 5: Aggregated throughput vs. number of users

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] “Overview of 3gpp release 8,” 2008. Available from http://www.3gpp.org/Release-8; accessed 1 April 2010.

[2] L. R. de Temino, G. Berardinelli, S. Frattasi, and S. Mogensen, “Channel-aware scheduling algorithms for sc-fdma in lte uplink,” in *Personal, Indoor and Mobile Radio Communications, 2008. IEEE 19th International Symposium, Cannes*, pp. 1–6, December 2008.

[3] H. Myung and D. Goodman, *Single Carrier FDMA: A New Air Interface for Long term Evolution*. West Sussex, UK: Wiley & Sons, 2008.

[4] F. Calabrese, P. Michaelsen, C. Rosa, M. Anas, C. Castellanos, D. Villa, K. Pedersen, , and P. Mogensen, “Search-tree based uplink channel aware packet scheduling for utran lte,” in *Vehicular Technology Conference, 2008, VTC Spring 2008, IEEE*, pp. 1949–1953, May 2008.

[5] H. Myung, O. Kyungjin, L. Junsung, and D. Goodman, “Channel-dependent scheduling of an uplink sc-fdma system with imperfect channel information,” in *Wireless Communications and Networking Conference, 2008, Las Vegas, NV*, pp. 1860–1864, April 1986.

[6] H. Myung, J. Lim, and D. Goodman, “Single carrier fdma for uplink wireless transmission,” *IEEE Vehicular Technology Magazine*, vol. 1, pp. 30–38, September 2006.

[7] G. T. 25.913, “Requirements for evolved utra and evolved utran (e-utran), release 8,” 2008. Available from http://www.3gpp.org/ftp/Specs/html-info/25913.htm; accessed 1 April 2010.

[8] J. Lim, H. G. Myung, K. Oh, and D. J. Goodman, “Proportional fair scheduling of uplink single-carrier fdma systems,” in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) 2006, Helsinki, Finland*, September 2008.