Adaptive Scheduling for MIMO Wireless Networks: Cross-Layer Approach and Application to HSDPA

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***Abstract*— In this paper, we consider the scheduling problem in multiple-input multiple-output (MIMO) wireless networks. The main important characteristic of an optimal scheduler is to maximize throughput while servicing users in a fair manner. Herein, we formulate MIMO scheduling as a Generalized Assignment Problem (GAP) and propose a general solution for the GAP, namely, a Cross-Layer MIMO scheduler (CMS), which uses a novel Adaptive Proportional Fairness (APF) mapping approach in conjunction with a new Fast Transmit Antenna Selection (FTAS) technique, to determine the set of users to transmit to and the antenna over which the data associated to each user should be transmitted. The proposed scheduler is applied for packet transmission in High-Speed Downlink Packet Access (HSDPA), taking advantage of the use of adaptive modulation and coding while coping with the constraints on the maximum number of simultaneous codes a user equipment can support, the limited uplink signalling, and the absence of fast power control. Numerical results show that the proposed CMS provides up to 70% increase in total throughput compared to other scheduling schemes.**

***Index Terms*— Adaptive modulation and coding, antenna selection, cross-layer design, HSDPA, MIMO systems, scheduling.**

I. INTRODUCTION

MULTIPLE antennas at both ends of a transmission link establish a spatial MIMO system well-known to considerably increase the performance of wireless networks through the extra dimension offered in the spatial domain. Two types of MIMO systems can be distinguished, spatial multiplexing (SM) systems which exploit the multiple antennas as a means to increase the information data rate, and spatial diversity (SD) systems that aim to increase the reliability of the information transmission [1]. The concepts of SM and SD are also applicable in multiuser systems where by taking advantage of the independence of the fading statistics of different users, multiuser diversity (MD) can be exploited to increase the throughput of the system through simultaneous transmissions to a number of users. As throughput is not the only criterion that needs to be optimized and that a certain level of fairness needs to be guaranteed among active users, this gives rise to the following question: In a downlink SM system with multiple transmit antennas, how to schedule transmissions for the active users so as to maximize throughput while ensuring a high degree of service fairness. This question is particularly important in designing efficient scheduling protocols capable of extracting the MD gain that can be achieved in MIMO multiuser wireless networks.

It has previously been shown that the solution to throughput maximization in a single transmit antenna system is to transmit to one user at a time [2]. In this case, the function of the scheduler is to select at each transmission time interval (TTI) the user for which transmission would maximize a given objective function, whether it be solely throughput or a compound function of throughput and fairness. Under multiple antennas at the transmitter and SM, the scheduler needs not only to select the set of users to transmit to, an issue pertaining to the MAC layer, but also the antenna(s) over which the data associated to each user would have to be transmitted, which is basically a PHY issue. The scheduling problem becomes hence a user selection and an antenna assignment problem with the simplest solution consisting of scheduling transmissions in a round-robin fashion as considered in [3]. In [4], a more elaborate approach was proposed which consists of using the Hungarian method in assigning users' data to the transmit antennas. However, the suggested approach is suboptimal and yields an optimal assignment only when the number of antennas is equal to the number of active users.

In tackling the problem in a global and comprehensive manner, this paper presents a general formulation of the scheduling issue in a MIMO multiuser cellular network, proposes a framework for MIMO scheduling that exploits MD to jointly maximize throughput and fairness, applies the proposed framework to High Speed Downlink Packet Access (HSDPA), and provides performance analysis and comparisons that take into account the main characteristics and constraints of the aforementioned system. In particular, the scheduling problem is addressed as a Generalized Assignment Problem (GAP) [5] with a formulation that aims the maximization of a network utility function defined as a function of the individual utility of each user. In practice, a scheduling strategy needs to optimize both throughput and fairness which are two conflicting objectives, given that forcing fairness decreases the system's throughput and can result in a significant loss as the load of the system gets higher. Herein, we propose a new user utility function and advance a novel cross-layer scheduler design as a general solution for the GAP.

The proposed scheduling framework, called Cross-layer MIMO Scheduler (CMS), implements Adaptive Proportional Fairness (APF) mapping, a MIMO version of the recently introduced APF method [6], which maps the channel quality of each link (transmit antenna, user) into a utility function

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defined so as to control the throughput-fairness tradeoff in an adaptive and efficient way. Furthermore, CMS uses a new Fast Transmit Antenna Selection (FTAS) algorithm, an augmenting path technique that solves the GAP under study and provides the optimal users/antennas mapping – specifying the set of selected users and the mapping between these users and the transmit antennas – that maximizes the total utility of the network. Indeed, through performance evaluation and comparisons, the proposed CMS is shown to maximize the network utility and yield high network utilization in addition to its flexibility in adapting to the network characteristics and parameters, such as the antenna configuration (MIMO, SIMO), user propagating conditions, and the load on the network. To emphasize this, we apply our proposed framework to packet transmission in HSDPA [7].

HSDPA is an enhancement for the downlink of current 3GPP Wideband Code Division Multiple Access. In addition, the latest HSDPA release incorporates a major enhancement which consists of the use of multiple transmit and receive antennas (MIMO) [8]. Under consideration of the MIMO configuration, several techniques such as Space-Time Transmit Diversity (STTD) [9], SM through Bell-Labs V-BLAST [10], and Per Antenna Rate Control (PARC) [11], have been suggested for use in HSDPA [12]. Nevertheless, no appropriate multiuser scheduling has been proposed yet and none of the previously proposed solutions [3], [13], [14] have taken into consideration characteristics specific to HSDPA. In applying our CMS framework to HSDPA, we propose a scheduling technique tailored to the special characteristics and constraints of the system to further enhance its performance both in terms of throughput and fairness through the underlined joint user-selection/antenna-assignment process.

Hence, the main contributions of the MIMO scheduling framework introduced in this paper are fourfold: (i) formulation of the problem itself as a generalized assignment problem, (ii) definition of a user utility function that jointly considers throughput and fairness, (iii) proposal of a fast transmit antenna selection algorithm that jointly determines the set of users to transmit to and their mapping to the transmit antennas, and (iv) the advancement of a CMS solution tailored to the HSDPA specifications. Accordingly, we organized the remainder of the paper as follows. In Section II, we present a description of the CMS including formulation of the GAP and description of the APF mapping. Section III provides a detailed description of the FTAS algorithm. Section IV presents application of the CMS to transmission in HSDPA. Finally, simulation results and comparisons are provided in Section V, followed by concluding remarks given in Section VI.

II. CROSS-LAYER MIMO SCHEDULER DESIGN

A. Scheduling as a Generalized Assignment Problem

In a time-shared MIMO system that exploits MD, the function of the scheduler is to select, in each TTI, the set of users to transmit to, and determine the appropriate antenna on which each user's data should be transmitted, given the objective of maximizing the system's performance both in terms of throughput and fairness. We formulate this problem as a *Generalized Assignment Problem* [5], a constrained optimization problem, whose solution is a transmit assignment matrix that defines both the set of users to transmit to and the transmit antenna selected for each of these users.

Consider a MIMO system with N_T transmit antennas and K_A active users having data to be transmitted to. Each UE[1] is equipped with N_R receive antennas and implements Maximum Ratio Combining (MRC) [15]. We assume the Channel State Information (CSI)[2], between each transmit antenna i and UE j, to be available at the transmitter through a zero-delay error-free feedback channel, and define the corresponding link by a user utility function. Generalizing over all transmit assignment possibilities, we define the utility matrix $U = [u_{i,j}]_{i,j=1}^{N_\mathrm{T},K_\mathrm{A}}$, where element $u_{i,j}$ specifies the utility of choosing transmit antenna i for user j, i.e., the utility that would be achieved if the data corresponding to the j^th user were to be transmitted on the i^th antenna.

The generalized assignment problem can then be formulated as the maximization of the total utility of the system according to:

$$\max \quad \sum_{i=1}^{N_\mathrm{T}}\sum_{j=1}^{K_\mathrm{A}}\lambda_{i,j}\ u_{i,j} \tag{1}$$

$$\text{s.t.} \quad \sum_{i=1}^{N_\mathrm{T}}\lambda_{i,j} \leq 1, \qquad \forall j \in \{1,\ldots,K_\mathrm{A}\}; \tag{2}$$

$$\sum_{j=1}^{K_\mathrm{A}}\lambda_{i,j} \leq K_{\max}, \qquad \forall i \in \{1,\ldots,N_\mathrm{T}\}; \tag{3}$$

$$\lambda_{i,j} \in \{0,1\}, \tag{4}$$

where constraint (2) translates the hypothesis that a user can be assigned to only one transmit antenna, constraint (3) expresses the condition that a maximum of $K_{\max}$ users can be assigned to each transmit antenna, and $\lambda_{i,j}$ is the variable indicating whether user j is assigned to the i^th antenna or not. Finally, denote by K_S the maximum number of users that can simultaneously be served by the base station ($K_\mathrm{S} = K_{\max} \times N_\mathrm{T}$). In this formulation, there are specific reasons behind choosing a maximum of one antenna for each user. The solution for a general assignment of antennas to the active users requires a huge amount of uplink signalization. Indeed, for each user, the scheduler needs the CQI corresponding to each combination of antennas, out of 2^{N_T} possibilities. This requirement would not only introduce a high level of interference on the uplink, but also a large delay between reception of CQIs and the time assignment decisions should be made. Our solution as per the allocation of one antenna to a user simplifies the problem while addressing the practical implementation issues. In addition, it has previously been shown that when the number of users is high compared to the number of antennas, such assignment provides very good performance compared to the general one –in the sense of considering all possibilities– [16].

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[1] The terms "user" and "user equipment (UE)" are used interchangeably.

[2] We consider partial knowledge of the channel. Thus, the channel state is represented by a quality indicator, referred to as channel quality indicator (CQI).

Solution of the problem is defined by the Transmit Assignment Matrix (TAM)

$$G = [\lambda_{i,j}]_{i,j=1}^{N_{\mathrm{T}},K_{\mathrm{A}}}\,, \tag{5}$$

which maximizes the objective function (1) subject to the identified constraints (2)-(4). Note that for convenience, the TTI index is dropped from the formulation.

Given the objective of maximizing throughput while ensuring fairness among users, the function of the scheduler is to find the best TAM over short time scales (TTI), and to determine how resources should be shared among users over longer time scales. To appropriately define long-term sharing objectives, it is necessary to define a utility function that not only ensures a reasonable compromise between throughput and fairness, but also accounts for the time-variability in terms of transmission demands and propagating conditions. To this end, we define a utility function that ensures Adaptive Proportional Fairness (APF) among the users.

B. Adaptive Proportional Fairness Mapping

The APF module defines each link (i^{th} transmit antenna, j^{th} UE) by an utility value upon the instantaneous rate available over it, and generates the utility matrix $U = [u_{i,j}]_{i,j=1}^{N_{\mathrm{T}},K_{\mathrm{A}}}$ that will be used by the Fast Transmit Antenna Selection (FTAS) module to determine the optimal TAM, G^{*}, for the current TTI. In defining the utility function $u_{i,j}$, two parameters are of major importance, the instantaneous data rate available on link (i,j) which allows tracking the fast variations of the latter, and the user's throughput represented by the average data rate achieved by the user up to the TTI under consideration. Indeed, since resources are usually limited, transmission to all users at the same time is generally not possible and, hence, the utility of each user should incorporate both parameters so as to be able to control the tradeoff between maximizing the instantaneous total throughput of the system and maximizing long-term fairness between the users. In this vein, we define the utility function corresponding to the pair (i^{th} transmit antenna, j^{th} UE) as

$$u_{i,j} = \frac{(r_{i,j})^{e_j}}{R_j}, \tag{6}$$

where $r_{i,j}$ is the instantaneous rate between antenna i and UE j, R_j is the throughput of user j, and e_j is a weighted exponent used to force the proportional allocation between users so as to provide adaptive proportional fairness among them, even if they experience heterogenous channels. Furthermore, we define the maximum throughput that could be reached by a user j, if he were to be selected at each TTI, as

$$\overline{r}_j = \frac{1}{N_{\mathrm{T}}}\sum_{i=1}^{N_{\mathrm{T}}}\overline{r}_{i,j}, \tag{7}$$

where $\overline{r}_{i,j}$ represents the average data rate that could be achieved over the channel between antenna i and user j if the latter were to be selected at each TTI. This value can be updated at each TTI by averaging $r_{i,j}$, or represented by the data rate that is equivalent to the average Signal-to-Noise Ratio (SNR) over the corresponding channel.

Now, given that the available resources might not allow transmitting to all active users, but that only a subset of users S_u could be selected, the average values $R_j(t-1)$ are updated at each TTI t, taking into consideration the size of each user's traffic queue, according to the following rule:

$$\begin{cases} R_j(t) = (1-\alpha)R_j(t-1) + \dfrac{\alpha \min(r_{i,j}T_{\mathrm{s}}, Q_j)}{T_{\mathrm{s}}} & \\ & \text{if } j \in S_u \\ R_j(t) = (1-\alpha)R_j(t-1) & \text{if } j \notin S_u \end{cases} \tag{8}$$

where $\alpha \in [0,1)$ is a smoothing parameter, Q_j is the buffer size corresponding to user j, and T_{s} is the duration of a TTI. These average values $\{R_j\}_{j=1}^{K_{\mathrm{A}}}$ are updated in the APF bloc and used in the next TTI to determine the utility matrix and subsequently the corresponding TAM.

To achieve long-term fairness among users, updating of the control parameters e_j is performed at a larger time-scale. In this way, the scheduling algorithm has a chance to function properly and adapt its parameters only when necessary for the purpose of achieving proportional fairness between the users. Indeed, an updating of the control parameters is only relevant if the rates achieved by the users have reached stationary values upon which decisions about the level of fairness reached can be made. Such stationary values are determined through measurement of the changes exhibited by the throughput values (R_j) between consecutive TTIs. Specifically, the CMS checks in each TTI and for each user j if $|R_j(t) - R_j(t-1)| < \xi$, where ξ is a chosen parameter that specifies whether R_j has reached a stationary value or not. When a stationary state is reached for a given user j, the updating module verifies whether the difference between its normalized throughput, defined as $p_j = \dfrac{R_j}{\overline{r}_j}$, and the average value over all users, is within acceptable values defined by the interval $[-\varepsilon, \varepsilon]$. If the condition is not satisfied, the user control parameter e_j is updated according to:

$$\begin{cases} e_j = e_j + \Delta e \quad \text{if } \left(\dfrac{R_j}{\overline{r}_j} - \dfrac{1}{K_{\mathrm{A}}}\displaystyle\sum_{l=1}^{K_{\mathrm{A}}}\dfrac{R_l}{\overline{r}_l}\right) < -\varepsilon \\ e_j = e_j - \Delta e \quad \text{if } \left(\dfrac{R_j}{\overline{r}_j} - \dfrac{1}{K_{\mathrm{A}}}\displaystyle\sum_{l=1}^{K_{\mathrm{A}}}\dfrac{R_l}{\overline{r}_l}\right) > \varepsilon \end{cases} \tag{9}$$

where the choice of Δe depends on the speed of convergence sought and the desired strength of variations around the values at convergence, and ε is a tuning parameter that defines the degree of fairness sought. Indeed, the smaller the value of ε is, the smaller the discrepancy between the p_js would be, with a value of $\varepsilon \to 0$ indicating maximum fairness, expressed as equal proportional allocation of throughput between the users.

Under these definitions, the APF user utility function (6) encompasses the features of two popular scheduling strategies, namely, the PF policy, and the maximum Carrier-to-Interference Ratio (CIR) method. In fact, a choice of $e_j = 1$ makes the APF utility function equivalent to the decision metric used in the PF user selection criterion [17], and a value of $e_j = \infty$ results in the utility used in the maximum CIR method [18]. Thus, a choice of e_j between these two limits allows reaching a reasonable compromise between throughput and fairness and that, even when users exhibit heterogeneous propagating conditions as will be shown later. Indeed, by increasing the value of Δe, faster convergence to the steady state of R_j can be reached but with more oscillations around this value. In order to avoid these oscillations, we fix in our simulations Δe at 0.01. As for the smoothing parameter α used in the averaging process (8), we consider a value of 0.001 [17]. Finally, for $\Delta e = 0$ or $\varepsilon = \infty$, no updating is performed and the level of fairness achieved by the CMS is completely specified by the original values to which the control coefficients e_j, $j = 1, \cdots, K_{\mathrm{A}}$, are set.

III. FAST TRANSMIT ANTENNA SELECTION

The optimization problem under consideration can be formulated as finding, in each TTI, the TAM that maximizes the total utility of the system (1) under the identified constraints (2)-(4). In this section, we present our solution to the problem, namely, the Fast Transmit Antenna Selection (FTAS) algorithm which is characterized by its flexibility in adapting to practical transmission scenarios and configurations in terms of number of transmit antennas N_{T}, number of active users K_{A}, and the maximum number of users that can be assigned to a transmit antenna which is particularly important when UEs have different resource requirements and capabilities such as in HSDPA.

FTAS is an *Augmenting Path* technique that determines the optimal TAM G^* for a given TTI, taking as input information the utility matrix U produced by the APF module. To each element $u_{i,j}$ of U, the FTAS finds a corresponding value in G^*, namely $\lambda_{i,j} \in \{0, 1\}$ with the value $\lambda_{i,j} = 1$ indicating that user j is selected for the current TTI and that its data is to be transmitted on antenna i. Under the constraint that a user can be assigned to only one transmit antenna (2), each column of G^* can have only one non-zero value to which corresponds an utility value that contributes to the total utility achieved in the current TTI. Consequently, the function of FTAS can be seen as a search in U for the path specifying the positions of elements $u_{i,j}$ that maximize the objective function (1), that is, the sequence of positions with non-zero $\lambda_{i,j}$.

In the following, we describe the FTAS algorithm by distinguishing two operating conditions that are represented by the relationship between the *offer* and the *demand*. The offer is expressed as the maximum number of users that can simultaneously be served, K_{S}, and the demand is represented by the number of users awaiting transmission, K_{A}. In the first case, the offer is considered higher than the demand, i.e., $K_{\mathrm{S}} \geq K_{\mathrm{A}}$, and in the second, the demand is higher than the offer, i.e., $K_{\mathrm{A}} > K_{\mathrm{S}}$. The parameter K_{S} being directly related to the number of transmit antennas N_{T}, and the matrix U having size $N_{\mathrm{T}} \times K_{\mathrm{A}}$, the dimension that would be fully used by the algorithm is K_{A} in the first case, and N_{T} in the second. Denote by D the data matrix with number of columns the value that would be fully used by FTAS, hence D is equal to U or its transpose U^T, and consider the following notation and terminology:

- m: index of iteration, $1 \leq m \leq M$;
- $D^{(m)} = [d_{l,c}]_{l,c=1}^{A^{(m)},B}$ the data matrix in iteration m, with B the value that would fully be used by the algorithm;
- $P_n(k) = \{(l_1^n, 1), (l_2^n, 2), \ldots, (l_k^n, k)\}$: path n from column 1 to column k in matrix $D^{(m)}$, where (l_c^n, c) consists of the pair (line index, corresponding column);
- $L_n(k) = \{l_1^n, l_2^n, \ldots, l_k^n\}$: sequence of line indices corresponding to the n^{th} path $P_n(k)$, with $C_{k,n}(\mathrm{x})$ the number of times a value x appears in the sequence $L_n(k)$.
- $S(k) = \cup P_n(k)$: list of surviving paths from column 1 to column k, with cardinality $\mathcal{C}(S(k))$;
- $Z^{(m)}$: group of surviving paths with cardinality $\mathcal{C}(Z^{(m)})$;
- $T(P_n(k)) = \sum_{(l,c)\in P_n(k)} d_{l,c}$: weight of the path $P_n(k)$.

Algorithm 1 : Fast Transmit Antenna Selection (FTAS)

```
INPUT: Utility Matrix $U$.
OUTPUT: Transmit Assignment Matrix $G^*$.
INITIALIZATION:
$G^* \leftarrow [0]_{i,j}^{N_{\mathrm{T}},K_{\mathrm{A}}}$, $m = 0$
if $K_{\mathrm{S}} \geq K_{\mathrm{A}}$ then $D^{(0)} \leftarrow U$, $M \leftarrow 1$
else $D^{(0)} \leftarrow U^T$, $M \leftarrow K_{\max}$
$S(0) = \{\{(1,1)\}, \{(2,1)\}, \ldots, \{(A^{(0)}, 1)\}\}$
PROCEDURE:
for $m = 1$ to $M$ do
    Generate sub-matrix $D^{(m)}$ by deleting in $D^{(m-1)}$ lines
    already used in the optimal path of iteration $(m-1)$;
    Order columns of $D^{(m)}$ in the descending order in
    terms of the highest utility value in each column;
    for $k = 1$ to $B$ do
        Compute $T_{\mathrm{r}}^{(m)}(k)$
        $q \leftarrow 0$
        for $n = 1$ to $\mathcal{C}(S(k-1))$ do
            for $l = 1$ to $A^{(m)}$ do
                if $C_{k,n}(l) \leq M - 1$ then
                    $P_q(k) \leftarrow \{P_n(k-1), (l, k)\}$
                    $q \leftarrow q + 1$
                end if
            end for
        end for
        $S(k) \leftarrow \bigsqcup_{n=1}^{q} P_n(k)$
        for $\{P_u(k), P_v(k)\} \in S(k)$ do
            if $[L_u(k) = L_v(k)$ & $T(P_u(k)) < T(P_v(k))]$
                $\|$ $[T(P_u(k)) < \max_n\{T(P_n(k))\} - T_{\mathrm{r}}^{(m)}(k)]$
            then
                $S(k) \leftarrow S(k) \setminus P_u(k)$
            end if
        end for
    end for
    $Z^{(m)} \leftarrow S(B)$
end for
for each path $P \in \bigsqcup_{p=1}^{C(Z^{(m)})} Z^{(p)}$ do
    for $(i, j) \in P$ do
        if $K_{\mathrm{S}} \geq K_{\mathrm{A}}$ then
            $\lambda_{i,j} \leftarrow 1$
        else
            $\lambda_{j,i} \leftarrow 1$
        end if
    end for
end for
```

Starting with a set of initial conditions, the algorithm iterates on m until the stopping condition is met and the optimal TAM found. The FTAS is represented in its general form in Algorithm-1 which takes into consideration the two aforementioned cases. Depending on the relationship between K_{S} and K_{A}, FTAS executes a number of compulsory steps, $M = 1$ times if $K_{\mathrm{S}} \geq K_{\mathrm{A}}$, and $M = K_{\max}$ times when $K_{\mathrm{A}} > K_{\mathrm{S}}$. Moreover, FTAS includes a number of optional steps (11, 13 and 26) which are introduced to determine G^* while avoiding unnecessary computations, thus limiting the complexity of the approach. In particular, the first optional step represents permutation of the data matrix columns so as to position them in the descending order in terms of the highest utility value of each column k ($\max\limits_{l=1,\cdots,A^{(m)}} d_{l,k}$), and the last optional steps consist in using the metric

$$T_{\mathrm{r}}^{(m)}(k) = \sum_{s=k+1}^{B} \max_{l=1,\cdots,A^{(m)}} d_{l,s}, \qquad (10)$$

defined as the maximum remaining weight, to quickly eliminate paths that would not lead to the optimal TAM.

In each iteration m, the data matrix $D^{(m)}$ and the metric $T_{\mathrm{r}}^{(m)}(k)$ are updated based on the result of the previous iteration. Specifically, $D^{(m)}$ is a sub-matrix of $D^{(m-1)}$ generated by deleting in the latter, the lines already used in the optimal path found at iteration $m-1$, with the exception that $D^{(0)} = U$ in the first case ($K_{\mathrm{S}} \geq K_{\mathrm{A}}$) and $D^{(0)} = U^T$ in the second ($K_{\mathrm{A}} > K_{\mathrm{S}}$). In the following, we present simple examples to describe in detail the operation of the algorithm for each of these cases.

A. Operation of the FTAS Algorithm When $K_{\mathrm{S}} \geq K_{\mathrm{A}}$

Owing to the fact that only one iteration is needed in this case, index m is dropped for a simple illustration of the operation of the algorithm. The input data matrix is $D = U$ and for each column k of D, $k = 1, \cdots, K_{\mathrm{A}}$, the algorithm generates all possible paths $P_n(k)$, taking as a starting point the surviving paths obtained at the previous column, $S(k-1)$. The weight $T(P_n(k))$ is calculated for each path. Then, a test is performed to check if a pair (user k, transmit antenna l) belongs to more than one path, in which case only the one with the highest value of $T(P_n(k))$ is included in the set of surviving paths. In addition, the algorithm eliminates, for column k, the surviving paths that would not lead to the optimal solution; i.e., paths having $T(P_n(k))$ less than $\left(\max\limits_n\{T(P_n(k))\} - T_{\mathrm{r}}^{(m)}(k)\right)$, along with those that do not satisfy constraints (2) and (3). At the last column, remaining paths $S(K_{\mathrm{A}})$ represent the solution to the problem (1), namely a number of paths, each having a corresponding assignment matrix, and all yielding the same total utility value. Denote by P^* the path chosen, matrix G^* is obtained using the mapping (11) that specifies the transmit antenna to which each of the K_{A} users will be assigned.

$$\begin{cases} \lambda_{i,j} = 1, & \forall (i,j) \in P^*, \\ \lambda_{i,j} = 0, & \forall (i,j) \notin P^*. \end{cases} \qquad (11)$$

We represent in Fig. 1, an example when the number of active users ($K_{\mathrm{A}} = 6$) is less than the number of possible simultaneous transmissions ($K_{\mathrm{S}} = 8$). Fig. 1(a) shows the initial input matrix U on which the optional step 13 for permutation of columns is performed (Fig. 1(b)), followed by the $T_{\mathrm{r}}^{(m=1)}$ computation for each column. As can be seen, execution of the FTAS algorithm produces two paths (Bold line and Dotted line) with the same total utility value. Hence, two transmit assignment matrices

$$G_1^* = \begin{pmatrix} 0\,0\,0\,0\,0\,0 \\ 1\,1\,0\,0\,0\,0 \\ 0\,0\,0\,1\,1\,0 \\ 0\,0\,1\,0\,0\,1 \end{pmatrix} \quad \text{and} \quad G_2^* = \begin{pmatrix} 0\,0\,0\,0\,0\,0 \\ 1\,1\,0\,0\,0\,0 \\ 0\,0\,0\,0\,1\,1 \\ 0\,0\,1\,1\,0\,0 \end{pmatrix}$$

can be chosen in this case. Here it is important to mention that even though multiple solutions with the same maximum utility may exist, non-uniqueness of the TAM does not represent a significant practical concern given that the procedure is executed at each TTI and that a user that has not been selected through a given choice for the TAM would likely be in the next TTI.

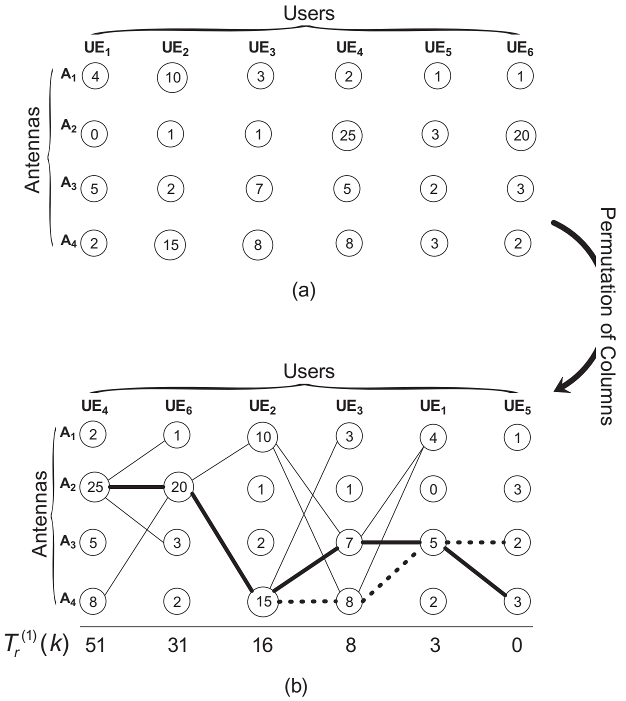


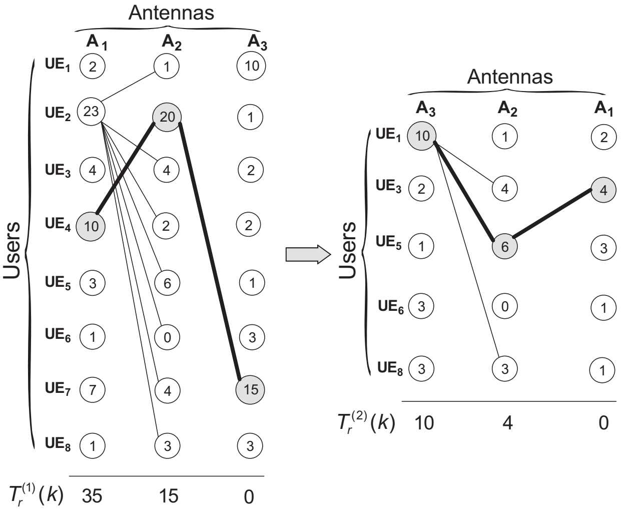
Fig. 1. An example illustrating the operation of FTAS when the number of active users K_{A} is less than the maximum number of simultaneous transmissions K_{S}.

B. Operation of the FTAS Algorithm When $K_{\mathrm{A}} > K_{\mathrm{S}}$

In this case, the input data matrix is $D = U^T$ and the path search procedure, as explained above, is repeated $M = K_{\max}$ times. At the last iteration, by combining the paths $Z^{(m)}$ for $m = 1, \cdots, K_{\max}$, the optimal path $P^* \equiv \bigsqcup\limits_{m=1}^{K_{\max}} Z^{(m)}$ is produced, and the assignment of the K_{S} users to the N_{T} antennas obtained according to:

$$\begin{cases} \lambda_{i,j} = 1, & \forall (j,i) \in P^*, \\ \lambda_{i,j} = 0, & \forall (j,i) \notin P^*. \end{cases} \qquad (12)$$

We show in Fig. 2 an example where the number of active users ($K_{\mathrm{A}} = 8$) is higher than the number of possible



(a) **(b)**

Fig. 2. An example illustrating the operation of FTAS when the number of active users K_{A} is higher than the maximum number of simultaneous transmissions K_{S}: (a) first iteration, (b) second iteration.

simultaneous transmissions ($K_{\mathrm{S}} = 6$). In this case, $M = 2$ iterations are needed to find the optimal TAM. Following the first iteration (Fig. 2(a)), only users who have not been selected/assigned are considered in the second one (Fig. 2(b)). The optimal path P^* is shown in Bold lines yielding the following transmit assignment matrix:

$$G^* = \begin{pmatrix} 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}.$$

C. A Word on Optimality and Complexity

The CMS produces the optimal assignment of antennas to UEs which maximizes the total utility of the network, defined by a path P^* that yields the maximum utility of the network. Optimality can be shown using a recursive method. Indeed, if there exists an other optimal solution or assignment, such solution can be mapped to a path P^+ in the matrix D. However, given that the CMS keeps, at each step (column k), only the paths which could survive until the last column, the optimal path selected by CMS is guaranteed to have the maximum weight, and as such any other possible path, such as path P^+, cannot provide a higher network utility.

Complexity computation of CMS depends on the operating case and can be assessed as a function of the number of operations (NOP). However, given that the number of maximum users that can be assigned to each transmit antenna, $K_{\max}$, introduces only a multiplicative coefficient to the NOP, the complexity mainly depends on the values of K_{A} and N_{T} upon which two cases can be distinguished. In the first ($N_{\mathrm{T}} \geq K_{\mathrm{A}}$), NOP is given by $\mathcal{O}(K_{\mathrm{A}}^2 . \frac{N_{\mathrm{T}}^{K_{\mathrm{A}}}}{K_{\mathrm{A}}!})$, and in the second ($K_{\mathrm{A}} \geq N_{\mathrm{T}}$), NOP is given by $\mathcal{O}(N_{\mathrm{T}}^2 . \frac{K_{\mathrm{A}}^{N_{\mathrm{T}}}}{N_{\mathrm{T}}!})$. In general, complexity is an exponential function of N_{T} and K_{A}. However, it is more usual that the number of users K_{A} is larger than the number of available antennas N_{T}. Consequently, the complexity becomes a polynomial function of K_{A}, which makes CMS a non-complex and fast solution to the GAP problem (1).

IV. SCHEDULING IN MIMO HIGH-SPEED DOWNLINK PACKET ACCESS

We now apply the CMS framework for transmission in HSDPA. Indeed, HSDPA introduces some characteristics, such as the use of Adaptive Modulation and Coding (AMC), the limits on the spreading codes and on the MIMO CSI, that need to be taken into consideration in the scheduler's design. In this section, we present the main features of HSDPA and advance a CMS solution tailored toward the HSDPA constraints. In particular, a new CSI signalling that copes with the limited resources is proposed for the MIMO configuration.

A. High Speed Downlink Packet Access (HSDPA)

HSDPA introduces two new physical channels for the downlink, namely, the High Speed-Downlink Shared Channel (HS-DSCH) and the High Speed-Shared Control Channel (HS-SCCH), and one for the uplink, that is, the High Speed-Dedicated Physical Control Channel (HS-DPCCH). The HS-DSCH is a shared channel that uses a small spreading factor value of 16 to allow high-speed transmissions, and AMC as a link adaptation method instead of power control. The HS-SCCH is used to transmit parameters such as channelization codes, and Transport Block (TB) size based on which UEs determine the modulation order and coding rate that were used by the base station (Node B). On the uplink, the HS-DPCCH carries the feedback signalling related to downlink HS-DSCH transmission, namely, the Hybrid-Automatic Repeat reQuest Acknowledgment (HARQ-ACK), and the CQI. The CQI value is used to determine the TB size [19], and consequently the transmission rate that the channel can support for the next TTI.

In addition, HSDPA UEs are classified upon their capabilities in terms of the maximum number of simultaneous HS-DSCH codes and the modulation order a UE can support. Twelve categories are distinguished, eight of which (1–6, 11 and 12) are characterized by a processing capability of at most 5 simultaneous spreading codes. In practice, more than 70% of the UEs will belong to these categories, an issue that needs to be taken into consideration in the design of the scheduler [7]. Finally, the HS-DSCH channel is allocated 10 spreading codes and the remaining codes are used by the pilot channels, Primary Common Pilot Channel (P-CPICH) and Secondary Common Pilot Channel (S-CPICH), and the Common Control Channel (HS-SCCH).

The MIMO configuration in HSDPA was first proposed in Release 5, and effectively included in Release 6 [8], [12]. Different MIMO schemes were suggested, with the majority proposing to take advantage of the SD gain that can be achieved by allocating all transmit antennas to one user at a time so as to improve the corresponding channel quality. However, because of the limitation on the number of simultaneous spreading codes a UE can handle, most users cannot benefit from the signal-to-noise and interference ratio (SNIR) gain that can be achieved through the use of SD, and as a result, their data rates cannot be increased beyond a certain

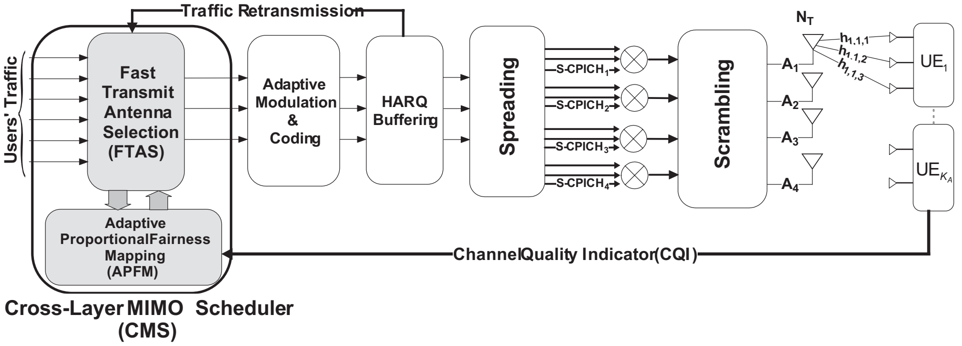


Fig. 3. General architecture of the MIMO HSDPA transmission procedure including the cross-layer MIMO scheduler (CMS).

limit. Indeed, whether only one transmit antenna is available for these users or that MIMO SD is implemented, it is not always possible to improve their throughput even though their corresponding channels might allow high transmission rates to be used at the base. As such, the use of SM, by multiplexing the data of different users over all antennas in each TTI, is a more suitable choice that not only allows to accommodate users with different capabilities but also to efficiently use the available resources and improve the multiuser diversity gain. Herein, we propose the use of SM without any SD. In fact, it has previously been shown that when the base station has partial CSI, transmitted by the UEs to the base, then schemes exploiting SM outperform these attempting to combine the advantages of both techniques [20].

Tailored towards the MIMO configuration of HSDPA, the proposed CMS is adapted so as to take into consideration the above-mentioned constraints for an efficient utilization of the available resources. In particular, the CMS overcomes the 10-code limitation by using the same set of codes over each transmit antenna, and differentiating the traffic carried over each through the use of scrambling codes. In addition, if there are some users able to process 10 simultaneous codes, the CMS can be adapted by assigning a transmit antenna to one user of such category, or to two users each with a capability of 5 codes. Moreover, instead of using the same modulation/coding scheme over all antennas, as in a STTD scheme, the CMS selects the one suitable for each link (transmit antenna, user) so as to satisfy the QoS of each user, based on the CQI value the UE feeds back to the transmitter.

B. MIMO Channel Quality Indicator

The CMS relies on the CSI of each link (transmit antenna, user) to determine the utility matrix, and hence the TAM for each TTI. However, the original CQI mapping [19] was designed for a single transmit antenna, and the size of the field used to represent a CQI value is 5 bits only, which makes signalization of different links in the same TTI impossible. In the following, we propose a CQI mapping and signalization that is suitable for the MIMO configuration.

Consider first the SISO configuration where for convenience the single transmit antenna is referred to by index i. In this case, the UE j computes the CSI upon the SNIR of the pilot channel (P-CPICH or S-CPICH) transmitted by antenna i, $SNIR_{i,j}^{\text{scpich}}$, and deduces the SNIR of the HS-DSCH channel according to [21]:

$$SNIR_{i,j}^{\text{hsdsch}} = \frac{SF^{\text{hsdsch}}}{\tau_{i,j}\ \log_2 M_{i,j}} \times \frac{\dfrac{1}{\min(K_{\text{S}}, K_{\text{A}})}}{\rho\left(\beta - \dfrac{1}{\min(K_{\text{S}}, K_{\text{A}})}\right) + \beta\ \dfrac{SF^{\text{scpich}}}{SNIR^{\text{scpich}}}}, \tag{13}$$

where β is the S-CPICH pilot power ($\beta = -10$dB), ρ is the code orthogonality factor, *SF* is the spreading factor, and $M_{i,j}$ and $\tau_{i,j}$ are respectively the modulation order and the code rate selected on the HS-DSCH channel between the transmit antenna i and UE j. $SNIR_{i,j}^{\text{hsdsch}}$ which ranges over 30dB, between -5dB and 25dB, is then mapped into one out of 30 possible CQI values according to the following rule:

$$\text{CQI}_{i,j} \simeq \min\left(\max\left(0, \lfloor SNIR_{i,j}^{\text{hsdsch}} + 6\rfloor\right), 30\right), \tag{14}$$

where $\lfloor\cdot\rfloor$ denotes the floor function.

The methodology proposed herein for the MIMO configuration consists in using a different pilot channel (S-CPICH) for each transmit antenna (Fig. 3). Each S-CPICH is scrambled by a different code and allocated the same amount of power, the pilot budget being evenly distributed over the N_{T} transmit antennas (-13dB in case of N_{T}=2). At each TTI, each UE j computes the SNIR corresponding to the link (transmit antenna i, UE j), $SNIR_{i,j}^{\text{hsdsch}}(t)$, using MRC over the UE's receive antennas according to:

$$SNIR_{i,j}^{\text{hsdsch}}(t) = \sum_{k=1}^{N_{\text{R}_\text{j}}} SNIR_{i,j,k}^{\text{hsdsch}}(t), \tag{15}$$

where N_{R_j} is the number of receive antennas at UE j. Then, for each link (i,j), $i = 1, \cdots, N_{\text{T}}$, the UE j calculates an average SNIR value, by averaging its $SNIR_{i,j}^{\text{hsdsch}}(t)$ values over a TTI window of size $N_{\text{av}} \geq N_{\text{T}}$ according to:

$$\overline{SNIR}_{i,j}^{\text{hsdsch}}(t) = \frac{1}{N_{\text{av}}} \sum_{l=t-N_{\text{av}}+1}^{t} SNIR_{i,j}^{\text{hsdsch}}(l). \tag{16}$$

$\overline{SNIR}_{i,j}^{\text{hsdsch}}(t)$ is then mapped into an average CQI value, $\overline{\text{CQI}}_{i,j}(t)$ using (14). The values $\{\overline{\text{CQI}}_{i,j}\}_{i=1}^{N_{\text{T}}}$ are then transmitted in a cyclic way through the HS-DPCCH feedback channel, thus providing the modulation order and coding rate that can be used by each transmit antenna i for a possible transmission to UE j in the next TTI.

Thus, after N_{av} TTIs, all the CQI values of the MIMO channel will be available at the base station, namely, the matrix $\left[\overline{\text{CQI}}_{i,j}\right]_{i,j=1}^{N_{\text{T}},K_{\text{A}}}$ needed to generate the utility matrix U. Note that even without the use of instantaneous CQI values at each TTI, the average CQI values provide acceptable prediction of coding and modulation schemes suitable for the next TTI, and that, with no significant loss in performance even when $N_{\text{av}} = 40$. Besides, due to the use of chase combining [22], retransmission of a packet must use the same coding and modulation as in its first transmission. Hence, in order to perform a retransmission, the acceptable value of the received $\overline{\text{CQI}}_{i,j}(t)$ must be equal to at least the value $\overline{\text{CQI}}_{i_0,j}(t_0)$ corresponding to the previous transmission/retransmission performed at t_0 from antenna i_0. Therefore, for HARQ retransmissions, a specific procedure as proposed in Algorithm-2, should be executed following the CQI mapping (14) in order to verify this requirement for each packet retransmission.

Algorithm 2 : CQI mapping for HARQ retransmissions

```
INPUT: $\overline{\text{CQI}}_{i_0,j}(t_0)$: CQI of last transmission, of the same packet of user $j$, performed at $t_0$ over transmit antenna $i_0$.
OUTPUT: $\overline{\text{CQI}}_{i,j}(t)$.
for $j = 1$ to $K_{\text{A}}$ do
    for $i = 1$ to $N_{\text{T}}$ do
        if $\overline{\text{CQI}}_{i,j}(t) \leq \overline{\text{CQI}}_{i_0,j}(t_0)$ then
            $\overline{\text{CQI}}_{i,j}(t) \leftarrow 0$
        else
            $\overline{\text{CQI}}_{i,j}(t) \leftarrow \overline{\text{CQI}}_{i_0,j}(t_0)$
        end if
    end for
end for
```

V. PERFORMANCE EVALUATION AND ANALYSIS

Hereafter, we present simulation results for the proposed Cross-layer MIMO Scheduler (CMS) and evaluate its performance in comparison with two scheduling approaches: the Proportional Fairness (PF) policy, and the best-user method [23]. The performance analysis is performed in terms of fairness and throughput. We consider HSDPA users of category 6, hence having 5-code limitations [19]. As considered in subsection II.A, we assume an error-free feedback of the CQIs given that best-user scheduling and CMS use the same CQI values in choosing the best antenna/user assignment and that both techniques will consequently be affected in the same way by feedback errors[3].

TABLE I

SUMMARY OF CHANNEL DISTRIBUTION PARAMETERS

User index	Rayleigh ($f_d = 5$Hz)	Shadowing (standard deviation)	$\overline{r}_j$ (kb/s)
UE-1	–	–	80
UE-2	–	–	80
UE-3	–	1 dB	80
UE-4	–	2 dB	80
UE-5	–	3 dB	80
UE-6	yes	4 dB	80
UE-7	yes	6 dB	80
UE-8	yes	8 dB	80

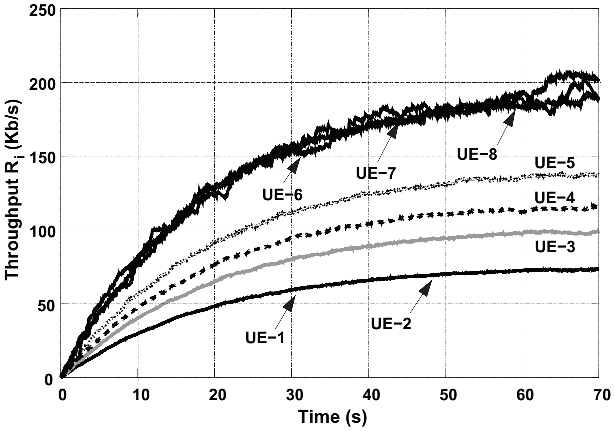


Fig. 4. Evolution of data rates $\{R_j\}_{j=1}^{K_A=8}$ with time when using the PF method in a SISO configuration.

Consider first the SISO configuration ($N_{\text{T}} \times N_{\text{R}} = 1 \times 1$) and a simple simulation scenario, chosen to assess the performance of CMS compared to the aforementioned policies, and show its high efficiency in improving fairness between users even when these exhibit heterogeneous propagating conditions. We consider $K_{\text{A}} = 8$ active users and assume that all are allocated the same transmission power, the only difference being the type of variations exhibited by the channel of each one (Rayleigh, Shadowing, or both). In Table I, we specify the channel model of each UE and provide the corresponding parameters used in the simulations. We present in Fig. 4 the throughput, R_j, achieved by each user as a function of time when using the PF algorithm. As observed, even if the users have the same power allocation available on their own channel and the same path loss allowing the same mean data rate, $\overline{r}_j$, (Tab. I) the PF method does not allocate throughput fairly among them. This is due to the difference in the variations exhibited by the channels of these users, namely, the difference in the variance associated to each channel distribution. The more the channel variations are, the higher is the throughput R_j achieved by the corresponding user. Comparing these results with the ones obtained using the proposed CMS (Fig. 5) shows how our technique outperforms the PF method through a fair throughput allocation despite the difference in the channel distributions of the different users or the underlying variances. This can be observed in Fig. 6 comparing the proportional throughput results of both methods. For example, examining these results shows how the PF policy allocates to UE-8 46% of its average data rate $\overline{r}_j$ whereas UE-1 gets allocated only 18% of the data rate its channel can support, a value that represents less than half the share corresponding to UE-8. On the other hand, using CMS, the allocation is between 26% and 28% for all users. Compared to the PF policy, CMS achieves fairness between users with heterogeneous channels and that with only 10% reduction in total throughput.

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[3] It is shown in [8] that CQI errors in the feedback channel do not significantly affect the throughput performance of the scheduler.

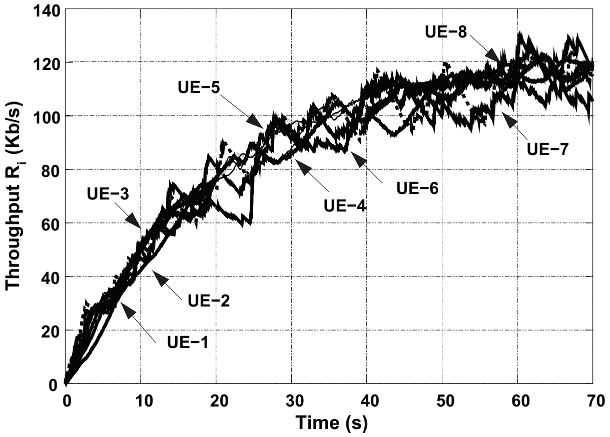

Fig. 5. Evolution of data rates $\{R_j\}_{j=1}^{K_A=8}$ with time when using the cross-layer MIMO scheduler (CMS) in a SISO configuration.

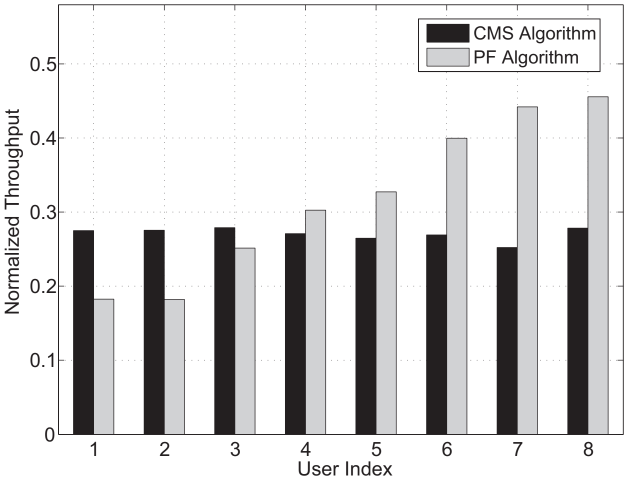

Fig. 6. Normalized throughput of each user: comparison between PF and CMS in the SISO configuration.

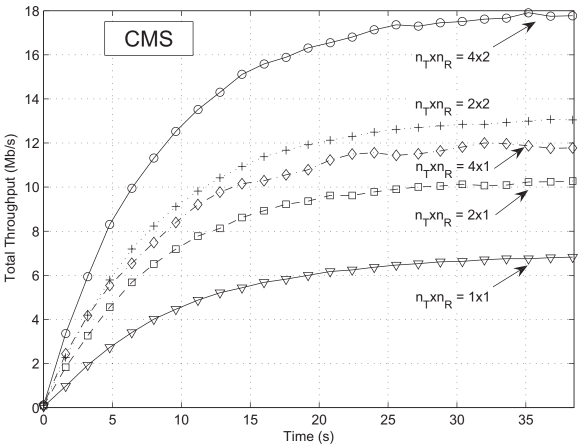

Fig. 7. The total throughput performance obtained using the cross-layer MIMO scheduler (CMS) for different antenna configurations ($N_{\mathrm{T}} \times N_{\mathrm{R}}$).

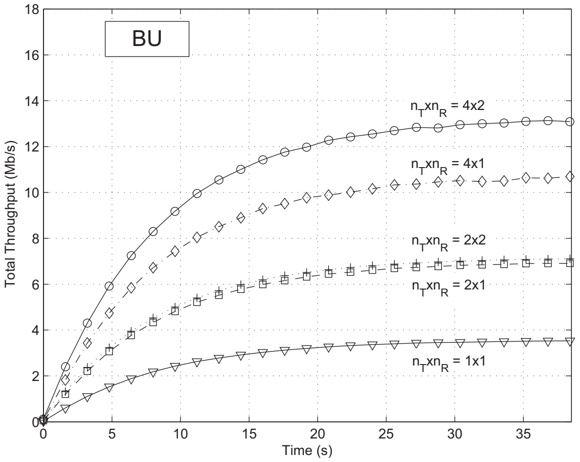

Fig. 8. The total throughput performance obtained using best-user (BU) scheduling for different antenna configurations ($N_{\mathrm{T}} \times N_{\mathrm{R}}$).

We now consider the MIMO configuration and evaluate the throughput performance of the proposed scheduler as compared with the above-mentioned approaches. The CMS has been studied for different antenna configurations, $N_{\mathrm{T}} \times N_{\mathrm{R}}$, load on the network, and traffic models. Herein, we consider Variable Bit Rate (VBR) video streaming traffic at 24frame/s [24], [25], with a Group of Picture (GOP) size equal to 12. The Intra frames (I), Predicted frames (P) and Bidirectional predicted frames (B) follow a lognormal distribution [26]. As for the MIMO configuration, we provide results for different antenna settings, where the number of transmit antennas $N_{\mathrm{T}} \in \{1, 2, 4\}$ and the number of receive antennas $N_{\mathrm{R}_j} = 1$ or 2, for $j = 1, \cdots, K_{\mathrm{A}}$ with $K_{\mathrm{A}} = 12$, and UEs belonging to category 6 [19]. Results corresponding to the SISO configuration are also presented to serve as a reference point. As for the channel, we consider correlated Rayleigh fading based on the MIMO channel model provided in [27]. We also consider slowly-moving users (3km/h) uniformly distributed within the cell, and following a random walk model. Taking into consideration the same total available transmit power, we compare the total throughput ($\sum_{j=1}^{K_{\mathrm{A}}} R_j$) obtained when using the proposed CMS (Fig. 7), with that obtained using the method presented in [23] in which the best-user, in terms of channel quality, is selected for each transmit antenna (Fig. 8). Analysis of these results shows that CMS outperforms the best-user method for all antenna configurations. For example, in the case of two antennas at both the transmitter and the UEs (2×2), the use of CMS yields a $6\mathrm{Mb/s}$ throughput increase over that obtained with the best-user method, and $\sim 3\mathrm{Mb/s}$ increase for the SISO case. Indeed, in the latter case, due to the fact that all users are limited by 5 simultaneous codes, the best-user method reaches the maximum throughput that could be achieved by a user ($\frac{7168bits}{0.002s} = 3.5\mathrm{Mb/s}$), while CMS yields approximatively the double ($6.8\mathrm{Mb/s}$) by allowing transmission to two users over the transmit antenna and in the same TTI, in addition to the use of the APF utility to provide high level of fairness; hence maximizing multiuser diversity gain and using all ten codes that are available over the antenna.

VI. CONCLUSIONS

We proposed a new scheduler for MIMO wireless networks, the Cross-layer MIMO Scheduler (CMS) which optimizes user's diversity over antennas and provides high throughput while servicing users in a fair manner. In the CMS design, the MIMO scheduling problem is formulated as a generalized assignment problem. CMS implements Adaptive Proportional Fairness (APF) mapping and a new Fast Transmit Antenna Selection (FTAS) technique to make an optimal selection of users and the assignment of their corresponding data to the transmit antennas. In the APF module, each user-antenna link is mapped into a user utility function defined in a way to be able to control fairness between users. The utility matrix generated by the APF module for the active users is then used by FTAS, an augmenting path technique that determines the transmit assignment matrix to be used by CMS in order to maximize the total utility of network. A CMS solution tailored toward HSDPA was also proposed, and shown to maximize the system's throughput while providing an acceptable level of fairness between the users. Simulation results showing the improvement in fairness achieved by the CMS compared to PF scheduling were provided. Compared to best-user scheduling, CMS was also shown to provide a higher efficiency even for the SISO configuration.

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