FIELD TRIAL RESULTS ON MULTI-USER MIMO DOWNLINK OFDMA IN TYPICAL OUTDOOR SCENARIO USING PROPORTIONAL FAIR SCHEDULING

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ABSTRACT

In this paper we present first real-time outdoor multi-user multi-antenna measurements based on system parameters close to 3GPP-Long Term Evolution. We demonstrate switching between various transmission modes in the downlink steered by a quantized feedback channel. Real time results show that an OFDMA proportional fair scheduler based on the quantized feedback achieves significant performance gains over a fixed OFDM-TDMA system. However, the proportional fair scheduler results in user starvation periods in the event of correlated feedbacks. To this end, we formulate a downlink scheduling problem with zero-starvation as a short term fairness [5] objective. This is an integer programming (IP) problem. In this paper, we present a simple heuristic algorithm for this problem for $K = 2$ users. Significant system sum rate gains are shown while still fulfilling the fairness objective.

1. INTRODUCTION

Multi-user MIMO systems in downlink have recently received widespread attention in wireless communications. These systems tend to exploit spatial fading diversity between multiple antenna terminals. In a broadband wireless system, the benefits of multi-user diversity is exploited with OFDM technique, where the entire bandwidth is subdivided into orthogonal subchannels.

With multi-user OFDM or OFDMA, many users are served in the same time slot, and user resource allocation is performed in frequency domain. Two classes of resource allocation are possible: fixed resource allocation [2] and dynamic resource allocation [3]. Fixed allocation schemes have a predetermined user resource allocation map irrespective of channel conditions. Dynamic resource allocation changes the user allocation map according to the channel conditions. For cellular systems, dynamic resource allocation is more attractive so that multi-user diversity can be exploited in closed loop operation. Standardisation bodies such as 3GPP-LTE [4], an evolutionary step of UMTS, have adopted MIMO-OFDMA downlink to enhance spectral efficiency in cellular systems. These new standards have incorporated dynamic resource allocation strategy in downlink OFDMA systems. In this paper, we investigate the performance of dynamic MIMO-OFDMA downlink using a real-time measurement test bed. We recently performed a LTE test bed measurement in Berlin. The measurement data from this campaign is used in this paper.

First, we illustrate the performance gains of multiple antenna systems in the downlink. We show that OFDMA significantly outperforms current OFDM-TDMA systems with multiple antenna terminals in outdoor scenario. In the prototype, we perform multi-user rate scheduling via OFDMA proportional fair algorithm [1], [6]. This dynamic resource allocation strategy promises long term resource fairness between users. However, we observe that with co-located users in similiar path loss conditions, the algorithm results in bursty TDMA behaviour. This in turn creates short term QoS issues because of prolonged periods without service.

Alternatively, we develop a new fair max rate scheduling approach, where each user requests to be guaranteed the broadband TDMA rate. Somewhat surprisingly, even with stricter short term goals, this scheduling approach achieves significant gains over OFDM-TDMA in sum throughput measure.

2. REAL TIME IMPLEMENTATION

The parameters set for the PHY implementation was chosen according to the working assumption around November 2005. We used 2 transmit antennas at the BS and 2 receive antennas at each of the UEs. The FFT/IFFT size is 2048 points with 1200 points used in the 20 MHz bandwidth. The smallest element of resource allocation termed a resource block (RB), consists of 25 sub-carriers and 7 long OFDM symbols (TTI). The cyclic prefix/ guard interval was 4.7 μs. 20 consective TTIs form a radio transmission frame of 10 ms. Frequency flat transmit power profile is adopted.

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3. SYSTEM MODEL

We consider an OFDM system in the downlink with K user equipments (UEs), each of which has m_R receive antennas and the base station (BS) has n_T transmit antennas. With OFDM, data signals are directly mapped in the frequency domain onto multiple sub-carriers. The relationship between the received and transmitted data on each sub-carrier is given by

$$\mathbf{y_k} = \mathbf{H_k x_k} + \mathbf{n_k} \tag{1}$$

where $\mathbf{x_k}, \mathbf{y_k}$ and $\mathbf{n_k}$ is the transmit data vector, received data vector and AWGN noise vector on sub-carrier k, respectively; $\mathbf{H_k}$ is the MIMO channel matrix with channel coefficients between all transmit and receive antennas.

3.1. Link Adaptation

Resources are used independently with specific modulation and coding schemes (MCS) for a specific user. In this way, the broadband system is decomposed into parallel user channels. The effective $SINR$ after MIMO detection at the receiver is calculated for each time-frequency resource block. This value acts as input for an adaptive bit loading algorithm. The calculation of the effective $SINR$ includes the estimated channel coefficients, the automatic gain control values, the estimated effective noise power and the spatial detector used at the receive side. The dedicated uplink control channel is protected with $\frac{1}{2}$ rate coding, a CRC, low order modulation BPSK/QPSK, DFT precoding and spatial diversity reception using cyclic delay diversity (CDD) at the UE and maximum ratio combining (MRC) at the BS. The uplink bandwidth is limited to 5 MHz bandwidth. The UE feedback rate is set to 9.6 Kbps.

The measurement prototype also supports antenna subset selection. The number of active antennas at each side of the link is varied by disconnecting one BS antenna and/or one UE antenna, allowing for four basic antenna setups for the downlink transmission: SISO, MISO, SIMO and MIMO. The receiver performs single stream or dual stream mode selection. It calculates the modulation coding scheme (MCS) based on achievable SINR for all transmit modes. The best combination of transmit mode and MCS is reported to the base station. In the MIMO configuration, the joint benefit of transmit mode selection and adaptive modulation is realised.

For single stream transmission, using channel vector $\mathbf{h_k}$ of dimension n_T, the MRC receiver filter is

$$\tilde{\mathbf{w}}_\mathbf{k} = \frac{\mathbf{h_k^H}}{|\mathbf{h_k}|^\mathbf{2}}, \tag{2}$$

For dual stream transmission mode, linear minimum mean squared error (MMSE) detector is applied. If the channel matrix of dimension $n_R \times n_T$ is denoted as $\mathbf{H_k}$, the MMSE receiver filter is given by,

$$\tilde{\mathbf{w}}_\mathbf{k} = \mathbf{H_k^H}[\sigma^\mathbf{2}\mathbf{I} + \mathbf{H_k H_k^H}]^\mathbf{-1}, \tag{3}$$

where σ^2 the noise power, $(.)^H$ the Hermitian transpose and $\mathbf{I}$ the identity matrix. The signal to noise plus interference ratio ($SINR$) for antenna i is calculated on average for each resource block (RB) in the physical layer. The post-detection $SINR$ is derived as

$$SINR_i^{MRC} = p_i \mathbf{h_i^H h_i} \sigma^2, \tag{4}$$

$$SINR_i^{MMSE} = p_i \mathbf{h_i^H}[\sigma^\mathbf{2}\mathbf{I} + \sum_{\substack{k=1\\k\neq i}}^{M} p_k \mathbf{h_k h_k^H}]^\mathbf{-1}\mathbf{h_i}, \tag{5}$$

where p_i is the transmitted power by antenna i. By this very basic link adaptation loop we achieve full flexibility in active antenna numbers at each end of the link. There is however a practical implementation issue in transmit mode selection. The transmission power loaded per stream is always fixed. This means that the radiated power from MIMO dual stream transmission is twice that of single stream transmission. This constraint has implications in our transmit mode selection probabilites in MIMO configuration.

3.2. Proportional Fair Algorithm

A broadband version of the the proportional fair scheduling algorithm [1], originally proposed for narrowband high data rate systems has been adopted.

Let $\mathbf{u_k}$ be the supportable rate vector for user k at time instant t. Let $r_k(t)$ be the allocated rate to user k. Then the implemented proportional fair algorithm for $K = 2$ users is as follows.

1. Calculate weight factors $w_k = \frac{\sum_{i=1}^{i=N} f^{i-1} r_k(t-i)}{\sum_{i=1}^{i=N} f^{i-1}}$. A typical value of N is equal to 128. f is the forgetting factor. Typical value of f is chosen to be 0.99.
2. Update $\tilde{\mathbf{u_k}} = w_k^{-1}\mathbf{u_k}$
3. Allocate resource blocks to users according to $\max[\tilde{\mathbf{u_1}}, \tilde{\mathbf{u_2}}]$. Let $\mathbf{y_k}$ be the allocated rate vector in time slot t for user k. Calculate total allocated rate as $r_k(t) = \mathbf{1^T y_k} \forall k = 1, 2$. Goto step 1 for next time instant $t + 1$.

The vector max operation $\max[\tilde{\mathbf{u_1}}, \tilde{\mathbf{u_2}}]$ performs max operation on corresponding elements of the vectors. Note that in the special case of weighting factor equal to 1, the proportional fair scheduler becomes a totally opportunistic max-rate scheduler. The smaller the f the more TDMA like behaviour is observed. In a round-robin OFDM-TDMA scheduler, the system sum rate for K users, $S_K(t)$, is given by

$$S_K(t) = \frac{\sum_{k=1}^{k=K} \mathbf{1^T u_k}}{K} \tag{6}$$

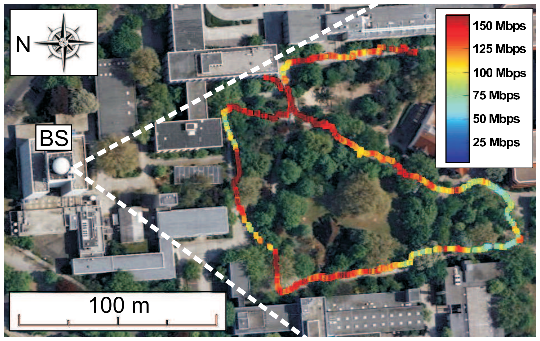

Fig. 1. Measurement Track

4. MEASUREMENT SCENARIOS

For the experiment we set up a multi-user outdoor scenario with one base station and two UEs. The two UEs are synchronized to the BS. The BS and each UE are equipped with two antennas. The BS employs cross polarised antennas$(+/-45°)$ which are placed on top of the building of the Heinrich-Hertz-Institute (HHI) at height of 60 m. The two UEs are placed in a van and the antennas, vertically and horizontally polarized, are mounted 30 cm above the roof of the van. The van was moving at slow velocity of about 3 to 5 km/h along a predefined route in the campus of the Technische Universitat Berlin. The two UEs are co-located and are separated by approximately 1 meter. The measurement track is depicted in **Fig. 1**.

5. RESULTS

5.1. SISO, SIMO and MIMO using TDMA

Experiments are conducted for the following configurations: SISO, SIMO (1x2) and MIMO (2x2). MIMO antenna configuration is capable of switching between single stream or dual stream transmit mode. The other configurations always transmit single stream. CQI values of modulation per resource block is fedback every radio frame to the BS by the UEs. Gains are obtained from frequency dependent link adaptation as well as transmit mode selection.

Fig. 2 shows system sum rate results for SISO, SIMO and MIMO configurations with a round robin TDMA scheduler. We straightaway see that MIMO antenna configuration increases the achievable sum rate over SIMO by 80 %.

Further, we also measure the gains of multi-user scheduling with $K = 2$ users using a frequency dependent proportional fair scheduler [1]. Results show that two-user diversity increases the sum rate by approximately 20 % as compared to a single user scenario.

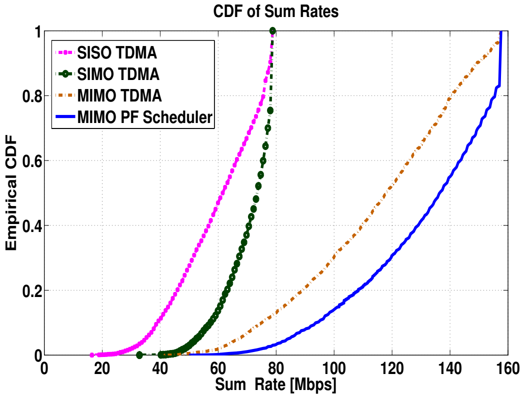

Fig. 2. Sum throughput comparison for various antenna configurations

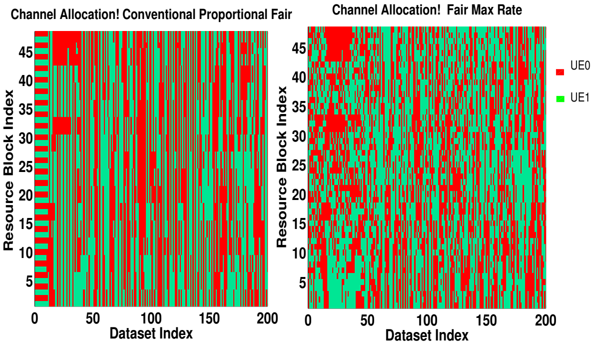

Fig. 3. Snapshot of user subchannel allocation

5.2. Short term fairness objective

Fig. 3 shows a snapshot of user dynamic subchannel allocation in the OFDMA system varied over time. The conventional PF scheduler shows over-assignment to one user within each OFDMA symbol, and therefore resembles an opportunistic TDMA scheduling. Here, we define starvation period as the number of radioframes between two service allocations to a particular user. In the scheduling snapshot in **Fig. 3**, left plot, we observe that the starvation window varies between 0 to 4 frames, where 0 indicates best fairness and 4 indicates the worst. In most real-time applications, prolonged periods without service offerings degrade the QoS experienced by a user and is therefore not desirable. Furthermore, the scheduler causes very bursty traffic for individual users even though it satisfies a resource-fair allocation over longer periods. In addition, as a result of quantized feedback correlations, one would also intuitively expect the starvation periods to increase with the number of users.

5.3. Constrained Max-Rate Problem

To solve the short term user satisfaction problem mentioned in the previous section, we here introduce a stricter short term rate constraint in the opportunistic max-rate scheduler. Let $\mathbf{u_1}, \mathbf{u_2}$ be the supportable rate vectors and $\mathbf{x_1}, \mathbf{x_2}$ be the decision vectors, for two users in the downlink. Then the resource allocation problem with strict fairness constraint becomes,

$$\begin{aligned} &\max \mathbf{u x^T} \\ &\text{Subject to } \mathbf{A x^T} > \mathbf{b^T}, \\ &\text{where } \mathbf{x} = \left[\begin{array}{cc} \mathbf{x_1} & \mathbf{x_2} \end{array} \right], \\ &\mathbf{u} = \left[\begin{array}{cc} \mathbf{u_1} & \mathbf{u_2} \end{array} \right] \\ &\mathbf{b} = \left[\begin{array}{cc} \alpha_1 \mathbf{1^T u_1} & \alpha_2 \mathbf{1^T u_2} \end{array} \right], \\ &\mathbf{A} = \left[\begin{array}{cc} \mathbf{u_1} & \mathbf{0} \\ \mathbf{0} & \mathbf{u_2} \end{array} \right], \\ &x_{1i}, x_{2i} \in \{0,1\}, x_{1i} + x_{2i} < 2, \\ &\alpha_1 + \alpha_2 < \frac{\mathbf{1^T u_1} + \mathbf{1^T u_2} - \max\left[\mathbf{u_1} \cup \mathbf{u_2}\right]}{\mathbf{1^T u_1} + \mathbf{1^T u_2}}. \end{aligned} \qquad (7)$$

α_1 , α_2 are the relative demand factors for the two users respectively. The demand factors ensure zero-starvation scheduling policy for a user if the supportable rate vector for that user is non-empty and are set pre-deterministically. The operator $\max\left[\mathbf{u_1} \cup \mathbf{u_2}\right]$ returns the largest element in both the vectors.

5.4. Fair Max-Rate Heuristic Algorithm

Here, we present a heuristic algorithm for the 1-0 integer programming problem in Eq(7).

1. Let $\mathbf{u_1}, \mathbf{u_2}$ be the supportable rate vectors for user 1 and user 2 respectively.
2. Obtain the opportunistic max-rate solution for inputs $\mathbf{u_1}, \mathbf{u_2}$. Store the computed decision vectors for two users as $\mathbf{x_1}, \mathbf{x_2}$. The corresponding rate allocation vectors are
   $\mathbf{y_1} = \mathbf{u_1}.\mathbf{x_1}, \mathbf{y_2} = \mathbf{u_2}.\mathbf{x_2}$.
3. Calculate user satisfaction scores, $S_k = \frac{\mathbf{1^T y_k}}{\alpha_1 \mathbf{1^T u_k}}$.
4. Check if $S_1 > \alpha_1$, $S_2 > \alpha_2$. If yes , terminate. Otherwise, initialise resource block priority vector $\mathbf{p_k}$, for the user with lower score, indexed as k. The priority vector contains resource block indices of zero components in $\mathbf{x_k}$, sorted in descending order of spectral efficiencies.
5. Assign the resource block with maximum priority, j, to user k by setting $x_{kj} = 1$. Remove the resource block from the priority vector $\mathbf{p_k}$. Update the scheduled rate allocation vectors $\mathbf{y_1}, \mathbf{y_2}$. Repeat Step 3. Break if $\mathbf{p_k}$ is empty.

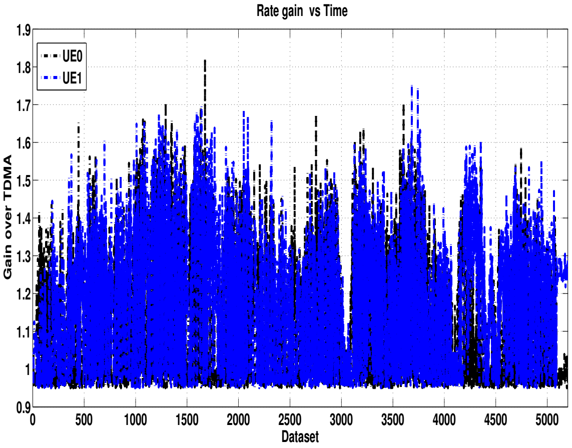

Fig. 4. Rate Fluctuations over time

This algorithm benefits in starting from a max-rate solution and therefore, strives not to sacrifice system sum-rate to achieve short term QoS goals.

If the minimum user allocation target rate is their corresponding TDMA rate, then the following relative demands are used

$$\alpha_k = \frac{\mathbf{1^T u_1} + \mathbf{1^T u_2} - \max\left[\mathbf{u_1} \cup \mathbf{u_2}\right]}{2[\mathbf{1^T u_1} + \mathbf{1^T u_2}]}, \quad k = 1, 2 \qquad (8)$$

On the other hand, in case the sum of relative demands $\alpha_1 + \alpha_2 \geq 1$, it introduces resource scarcity to the scheduler and the algorithm does not apply for those demands. In that case, the algorithm is applied after modifying the relative demands. This is done by performing max-min heuristic on α_k, such that $\alpha_1 + \alpha_2 < 1$. The same algorithm is applied on the modified relative demands. This approach in effect transforms the resource constraint to demand constraint.

5.5. Algorithm Performance

Fig. 4 illustrates the performance of the fair max-rate scheduler using $\alpha_1 = \alpha_2 = 0.48$, a demand scenario where users are guaranteed their respective OFDM-TDMA rate. The plot shows that both the users get approximately allocated their supportable TDMA rate in every radio frame. This fairness plot over time shows the short term rate satisfaction for users. For co-located users this in turn provides a fair long term rate to both the users.

The short term rate satisfaction is further characterised by the CDF in **Fig. 5**. It is observed that a totally opportunistic scheduler, red lines, have a long tail. This is because at

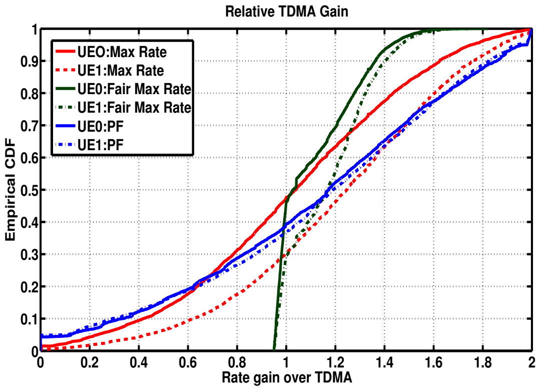

Fig. 5. Short term satisfaction relative to a TDMA scheme. (Red) Max-Rate Scheduler (Blue) Proportional fair scheduler (Black) Fair Max-Rate Scheduler

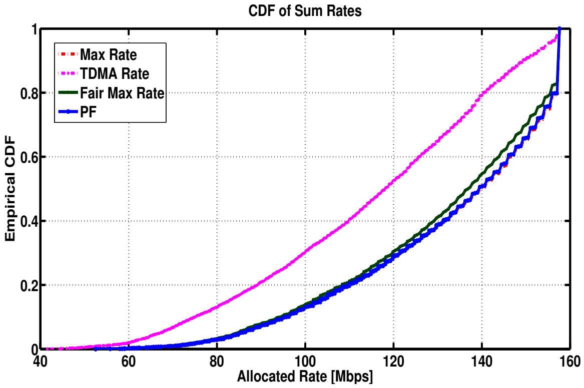

Fig. 6. System Sum Rate Performance (Red) Max-Rate Scheduler (Blue) Proportional fair scheduler (Black) Fair Max-Rate Scheduler (Pink) Round-robin TDMA

few instances the second user does not receive any resource allocation. However, it is observed that the proportional fair scheduler, blue lines, have even longer tail than the max-rate scheduler. This is because a purely time based window, refer section 3.2, is used by the PF algorithm. This time weighting window suppresses FDMA behavior. The longer tail has a negative QoS effect and degrades real time user rate experience. The fair max rate scheduler, black lines, is designed to enhance the short term user satisfaction. It has a clipped tail and guarantees approximately a TDMA rate. Nevertheless, tail clipping sacrifices higher rate gains for individual users. One would then wish to see the effect of this development on the absolute system sum rate. For this purpose, we show the sum rate characteristic in **Fig. 6**. Proportional fair scheduler matches the sum rate performance of max-rate scheduler for two co-located users. Note that, the PF scheduler achieves this performance via further extending the tail in the relative TDMA measure. The fair max-rate algorithm sacrifices some of the system sum rate gains for user satisfaction. However, this loss in system sum rate is observed to be neglible. The channel allocation table is shown in **Fig. 3**. It now shows a more FDMA behaviour with service offerings to both users in every OFDMA radio frame.

6. CONCLUSION

The paper demonstrated the gains of dynamic MIMO-OFDMA downlink using real time test bed measurement results. Results also confirmed that substantial system throughput gains are achieved using muliple antennas in a cellular environment. The measurement scenario involved two co-located users with correlated path loss moving in LOS conditions. In these conditions, it was observed that just a time windowed proportional fair scheduler is not ideal for QoS requirements. Accordingly, we introduced a relative throughput gain measure over OFDM-TDMA. A fair max rate scheduler was proposed to improve dynamic OFDMA scheduler performance in this criterion. The new OFDMA scheduler achieved significant sum-rate gains over conventional OFDM-TDMA scheme while also meeting the short term objectives.

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