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Joint Adaptive Modulation and MIMO Transmission for Non-Ideal OFDMA Cellular Systems

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***Abstract*—In this paper, a joint adaptive modulation and multiple-input multiple-output (MIMO) transmission scheme is considered. An efficient use of radio resources shall be based on channel state information at the transmitter (CSIT) to adjust the modulation order and MIMO transmission mode. A new suboptimal algorithm is proposed for link adaptation in a MIMO-OFDMA cellular system under spatially correlated fading and imperfect CSIT due to user mobility. Performance results are provided for the proposed solution under a long term evolution (LTE) downlink scenario. A substantial spectral efficiency gain is observed in contrast to the standalone transmission schemes.**

***Index Terms*—adaptive MIMO, adaptive modulation, rank adaptation, imperfect CSIT, user mobility, LTE.**

I. INTRODUCTION

The use of multiple-input multiple-output (MIMO) technology in wireless communications can be exploited either to increase the spectral efficiency or to improve the link robustness [1]. Orthogonal frequency division multiple access (OFDMA) based systems allow for applying different MIMO transmission modes to frequency sub-bands allocated to different users. Adaptive MIMO transmission is intended to select dinamically the optimum MIMO mode and modulation scheme in order to maximize the spectral efficiency while fulfilling the quality of service (QoS) requirements.

Several works have addressed a cross-layer design in adaptive MIMO-OFDMA systems. A multiuser scheduling method on a MIMO-OFDMA cellular system was proposed in [2]. An adaptive MIMO transmission scheme using channel rank was considered in [3][4]. However, at the best of authors knowledge, joint adaptive modulation and MIMO transmission has not been investigated under realistic conditions as spatial correlation and user mobility, which provokes imperfect channel state information at the transmitter (CSIT).

In this paper, we propose a new suboptimal algorithm for link adaptation in a MIMO-OFDMA cellular system under realistic conditions. Spatial correlation and imperfect CSIT have been considered in a long term evolution (LTE) downlink scenario. Modulation order and MIMO transmission mode are jointly selected in order to maximize the average spectral efficiency (ASE) while keeping the bit error rate (BER) below a certain target (BER_T).

The rest of this paper is structured as follows. System model is described in section II. The proposed scheme for link adaptation is addressed in section III. Section IV includes the simulation results and, finally, main conclusions are gathered in section V.

II. SYSTEM MODEL

A MIMO-OFDMA system with two transmit and two receive antennas (MIMO 2x2) is considered. The system model includes the following functionalities (see Fig. 1):

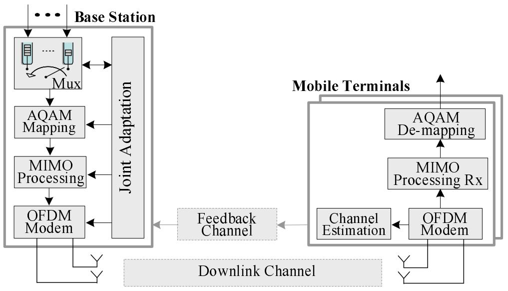

Fig. 1. System Model

- *Base Station*: user multiplexing, adaptive quadrature amplitude modulation (AQAM) mapping and MIMO processing are performed before the OFDM signal is transmitted. The total average transmit power is normalized to one and is equally distributed over the two antennas. A joint adaptation functionality selects dinamically the modulation order and MIMO transmission scheme to be applied to each frequency sub-band.

- *Downlink Channel Model*: the standard spatially correlated Rayleigh-faded multi-antenna channel model [5] [6] is here considered. Channel gain is modelled by a 2x2 complex matrix $\mathbf{H}$, so that the entries $\mathbf{H} = (h_{ij})$ denote the channel gain between the *j*th transmit and the *i*th receive antenna. Assuming the well-known Kronecker correlation structure [5], the channel matrix can be decomposed as $\mathbf{H} = \mathbf{R}_{rx}^{1/2}\mathbf{G}\mathbf{R}_{tx}^{1/2}$; where the entries of $\mathbf{G}$ are independent and identically distributed (i.i.d.) Gaussian random variables (RVs) with zero mean and unit variance. We assume the same antenna correlation factor (ρ) for transmit and for receive antennas, thus being the correlation matrices $\mathbf{R}_{tx}$ and $\mathbf{R}_{rx}$ identical and given by

$$\mathbf{R}_{tx} = \mathbf{R}_{rx} = \begin{bmatrix} 1 & \rho \\ \rho^* & 1 \end{bmatrix}. \qquad (1)$$

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A typical value of ρ in the range $0.3 \leq \rho \leq 0.9$ will be considered from previous studies on the antenna correlation for a typical suburban environment and linear antenna arrays [7].

Assuming the frequency domain baseband model, the received signal vector can be expressed as $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$; where $\mathbf{x}$ is the transmitted signal vector and $\mathbf{n}$ is the channel noise vector, whose entries are i.i.d. Gaussian RVs with zero mean and variance σ_n^2. We define the average SNR $\bar{\gamma}$ in terms of the transmit power constraint and the noise power as [8] $\bar{\gamma} \doteq 1/\sigma_n^2$.

- *Feedback Channel*: instantaneous channel state information (CSI) is reported from receivers to the base station through an ideal (error-free) feedback channel. The reported CSI is in the form of the instantaneous effective SNR γ_{eff} experienced at the receiver after the MIMO processing. Note that the MIMO link can be seen as an equivalent end-to-end SISO channel with an effective SNR γ_{eff} which depends on the applied MIMO scheme.

- *Mobile Terminals*: recovering of user data includes OFDM signal reception, MIMO processing, and AQAM de-mapping.

The following well-known MIMO schemes included in the LTE cellular standard [1] are considered for link adaptation:

- Transmit Beamforming (Tx BF)
- Precoded Spatial Multiplexing (Precoded SM)
- Space-Frequency Block Codes (SFBC)

Precoding based on singular value decomposition (SVD) of the channel matrix $\mathbf{H}$ is assumed for the closed-loop MIMO schemes (i.e. Tx BF and Precoded SM) [1]. For the transmit diversity schemes (i.e., Tx BF and SFBC), maximum ratio combining (MRC) is applied at the receiver as a means to improve the received signal quality from receive diversity.

III. PROPOSED SCHEME FOR LINK ADAPTATION

In this section, the proposed scheme for link adaptation is addressed. A joint adaptation of the modulation order and MIMO transmission is intended. The objective is to maximize the ASE by tracking the time-varying characteristics of the channel while fulfilling the predefined BER_T requirement.

We assume a minimum delay in the adaptation process of 1 time transmission interval (TTI). Therefore, the predefined BER_T requirement may be unfulfilled due to an outdated CSIT value. The channel information at the transmitter will be outdated when the channel time coherence, which is determined by the user mobility, is less than 1 TTI. Thus, we define different modes of operation depending on user mobility in order to assure the BER_T requirement to be fulfilled.

For clarification purposes, we first introduce two different adaptive modulation approaches which will be employed within the defined transmission modes. After that, the three defined MIMO transmission modes are described, and the adaptation among these modes is finally addressed.

A. Adaptive Modulation

A variable discrete-rate AQAM with constant average transmit power [9] is considered. Modulation order is adapted to keep the BER below a desired target (BER_T). Let γ_{AQAM} be the SNR metric used for adaptation (e.g. the reported instantaneous SNR). Then, a constellation of R_i bits per symbol is employed within the SNR region $\gamma_{AQAM} \in [\gamma_{i-1}, \gamma_i)$ with $i = 0, 1, 2, 3$ corresponding to outage, QPSK, 16QAM, and 64QAM, respectively. Hence, the posible number of bits per symbol are $R_i = 0, 2, 4, 6$ for $i = 0, 1, 2, 3$, with $\gamma_{-1} \doteq -\infty$, and $\gamma_3 \doteq \infty$.

A different adaptation process is performed depending on user mobility in order to assure the BER_T to be fulfilled. Hence, we adopt two different approaches: *fast AQAM* for low-medium mobility, and *slow AQAM* for high mobility scenarios. Differences between the two approaches are the adaptation rate, the SNR metric used for adaptation, and the design of thresholds γ_i. A more detailed explanation is given below.

1) Fast AQAM: the modulation is adapted instantaneously to track the fast variations of the channel, and the adaptation rate is 1 TTI. The metric used for adaptation is the reported instantaneous effective SNR γ_{eff} , i.e.$\gamma_{AQAM} = \gamma_{eff}$. With this approach, modulation is adapted to a certain channel gain γ_{eff} and, thus, the instantaneous or conditional BER (CBER) criterion is adopted [9] (i.e. $CBER \leq BER_T$). By following this approach, the instantaneous BER will be maintained below the target in a low-mobility scenario, i.e. with channel coherence time greater than 1 TTI. The design of thresholds γ_i is based on the BER performance of M-QAM modulations over a Gaussian channel, which is the equivalent channel for a given gain γ_{eff} .

2) Slow AQAM: in case of high mobility (short channel coherence time), CBER criterion cannot be fulfilled due to the outdated SNR report. The outdated CSIT may lead to a wrong selection of the modulation order. Alternatively, in this case the adaptation is based on the average SNR and is performed at a larger scale of channel variations. In other words, the adaptation rate is various magnitude orders greater than TTI (e.g. 1000 TTIs), and $\gamma_{AQAM} = \bar{\gamma}$. With this approach, instantaneous BER cannot be kept below the target due to the short coherence time of the channel, and thus, the average BER (ABER) criterion is adopted (i.e. $ABER \leq BER_T$). The design of thresholds will be based on the BER performace of M-QAM modulations over a Rayleigh-faded channel.

B. MIMO Transmission Modes

As mentioned above, user mobility is considered a crutial issue in the adaptation process since an outdated CSIT may cause the BER requirement to be unfulfilled. Besides, the performance of closed-loop MIMO schemes is specially degraded when the precoding information is outdated. Thus, we define three modes of operation depending on user mobility:

1) Rank Adaptation: This mode is applied in low-mobility scenarios and includes dynamic switching beween the two closed-loop MIMO schemes (Tx BF and precoded SM). The selection of the MIMO scheme and the modulation order is performed as shown in the flow chart of Fig. 2. The effective SNR $\gamma_{eff}^{(k)}$ is reported from the mobile terminals for each of the eigen-channels ($k = 1, 2$) [1]. The reported value is given by $\gamma_{eff}^{(k)} = \lambda_k$, where λ_k is the *k*th eigen-value of the matrix $\mathbf{H}^H\mathbf{H}$. Note that the spatial correlation is taken into account in the reported SNR value since the eigen-values of the matrix $\mathbf{H}^H\mathbf{H}$ will decrease as the correlation factor ρ increases.

The operation within this mode can be described as follows (see Fig. 2). First, *fast AQAM* is carried out based on the reported $\gamma_{eff}^{(k)}$ and the predefined BER_T requirement. As a result, the number of bits per symbol for the *k*th eigen-channel $R^{(k)}$ is obtained. If the second eigen-channel is in outage (i.e. $R^{(2)} = 0$), Tx BF is applied with $R^{(1)}$ bits per symbol. Otherwise, a new calculation of the bits per symbol for Precoded SM $R^{(k)*}$ is performed. In this case (Precoded SM), the effective SNR $\gamma_{eff}^{(k)*}$ is given by half of the reported value since half of the transmission power is used for each eigen-channel. Then, if the second eigen-channel is not in outage, precoded SM is selected with $R^{(1)*}$ and $R^{(2)*}$. By applying this algorithm, the rank of the tramsission (1 for Tx BF and 2 for precoded SM) is adapted to the instantaneous channel conditions in order to maximize the ASE.

2) SFBC + Fast AQAM: Since closed-loop schemes are very sensitive to an outdated precoding matrix, an open-loop scheme such as SFBC is employed as the user speed increases. However, the impact on performance of an outdated SNR report for adaptive modulation is much less than the one caused by an outdated precoding matrix. Therefore with a moderate mobility, SFBC transmission is applied together with *fast AQAM*. In this case, the reported effective SNR to be employed in the adaptation of modulation is given by

$$\gamma_{eff}^{SFBC} = \left(\frac{\bar{\gamma}}{2}\right) \|\mathbf{H}\|_F^2 \,, \tag{2}$$

where $\|\bullet\|_F^2$ denotes the squared Frobenius norm.

3) SFBC + Slow AQAM: For high mobility, *slow AQAM* is applied since the reported γ_{eff}^{SFBC} is outdated and the instantaneous BER restriction cannot be fulfilled. In this case, the reported γ_{eff}^{SFBC} is averaged over 1000 TTIs and the resulting $\bar{\gamma}_{eff}^{SFBC}$ is used to adapt the modulation. The SNR thresholds for this mode have been determined by means of simulations and can be found in Table I for several values of ρ.

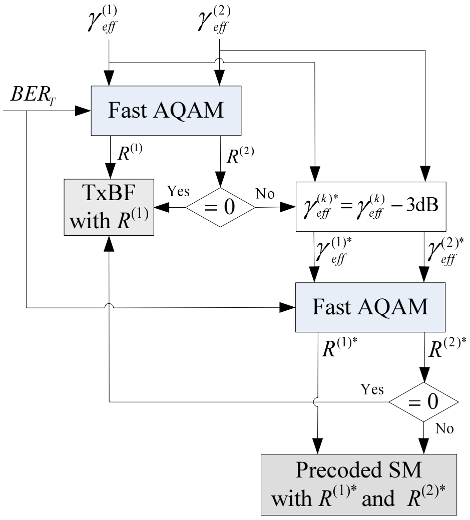


Fig. 2. Operation within *Rank Adaptation* mode

TABLE I
SNR THRESHOLDS FOR ADAPTATION IN *SFBC + Slow AQAM* OPERATION

BER_T	ρ	γ_0 (QPSK)	γ_1 (16QAM)	γ_2 (64QAM)
10^{-2}	0.3	6.25 dB	12.50 dB	18.20 dB
	0.7	7.50 dB	13.90 dB	19.65 dB
	0.9	9.70 dB	15.85 dB	21.35 dB
10^{-3}	0.3	10.35 dB	16.75 dB	22.60 dB
	0.7	11.90 dB	18.50 dB	24.35 dB
	0.9	14.50 dB	21.10 dB	26.85 dB
10^{-4}	0.3	13.40 dB	20.25 dB	26.00 dB
	0.7	15.45 dB	22.10 dB	27.90 dB
	0.9	18.55 dB	25.25 dB	31.10 dB

C. Adaptation Policy

Link adaptation is performed at two levels: dynamic and semi-static adaptation. On the one hand, dynamic adaptation is carried out on a TTI basis to track the fast variations of the channel. The *Rank Adaptation* mode and the *fast AQAM* procedure are examples of dynamic adaptation. On the other hand, semi-static adaptation is performed at a larger scale of channel variations, specifically once every 1000 TTIs, in order to track mid-term changes of the channel. The *slow AQAM* procedure is performed semi-statically.

Three modes of operation have been defined depending on user mobility. However, the user speed thresholds for switching between these modes have not been defined yet. In order to complete the adaptation rule, several simulations have been carried out to determine the maximum admissible speed for each mode of operation. As a result, a correspondance between user speed and transmission mode may be established for a given BER_T (see Fig. 3).

The overall link adaptation algorithm can be defined as follows. First, the base station selects one of the three MIMO transmission modes defined in the previous section. Switching between these modes of operation is performed semi-statically. The appropriate mode is selected for a given a QoS requirement (BER_T) and user speed, which can be derived at the

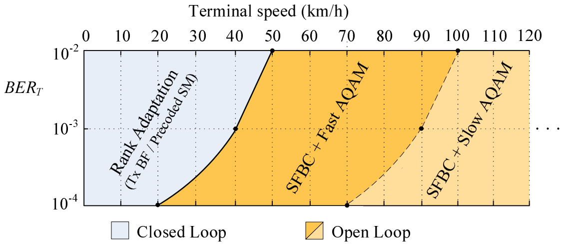


Fig. 3. Determination of the transmission mode as a function of mobility and BER_T requirement

base station from doppler shift measurements. Then, either fast or slow AQAM is performed as indicated within each transmission mode.

IV. SIMULATION RESULTS

The MIMO-OFDMA system described in previous sections have been implemented on C++ simulation software [10] in order to evaluate the performance of the proposed joint adaptation solution. The simulated MIMO-OFDMA system corresponds to an LTE downlink system [1] with the baseline antenna configuration (2x2). Main simulation parameters are listed in Table II. The power delay profile corresponding to a six-taps typical suburban channel [11] is considered.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Carrier frequency	1.8 GHz
Sampling frequency	30.72 MHz
System bandwidth	20 MHz
FFT size	2048
Number of data subcarriers	1200
Cyclic prefix length	144 samples
TTI (subframe duration)	1 ms
Target BER	10^{-3}
Mobile terminal speed	10-140 km/h
Adaptation rate	1 TTI

Several simulations have been carried out in order to evaluate the performance of the proposed link adaptation algorithm. Simulation results are organized in two groups. First, the three defined transmission modes are evaluated separately, i.e. without switching between them. Then, performance results of the proposed link adaptation including switching between transmission modes in a variable speed scenario are presented.

A. Standalone Transmission Modes

The ASE performance of the *Rank Adaptation* mode in comparison with its standalone schemes (Tx BF and Precoded SM) is depicted in Fig. 4. It is shown that the *Rank Adaptation* mode achieves always the maximum ASE and a substantial gain is observed when compared to the standalone schemes.

Fig. 5 and Fig. 6 show the ASE and BER performance, respectively, for each mode of operation with low spatial correlation ($\rho = 0.3$). The achievable ASE is depicted as a function of the average SNR $\bar{\gamma}$ for a given $BER_T = 10^{-3}$ in Fig. 5. To show the impact of mobility, the average BER is presented as a function of user speed in Fig. 6. It is shown that the *Rank Adaptation* mode achieves the maximum ASE. However, with this transmission mode the BER_T requirement

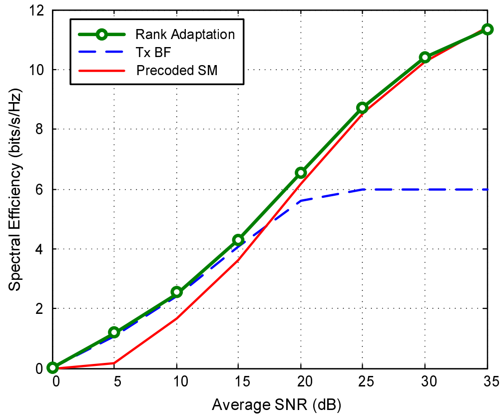


Fig. 4. Average spectral efficiency for *Rank Adaptation* mode in comparison with its standalone schemes (Tx BF and Precoded SM) for $BER_T = 10^{-3}$ and low-correlated channel ($\rho = 0.3$)

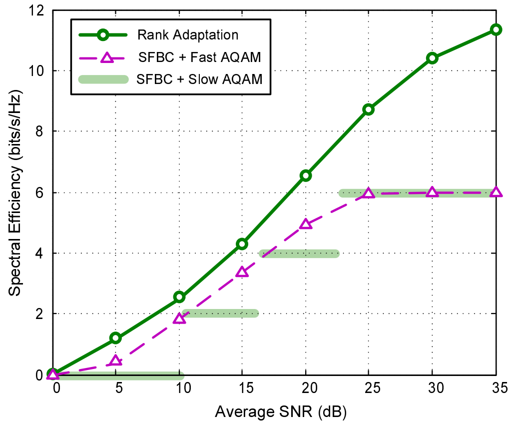


Fig. 5. Average spectral efficiency for the 3 defined transmission modes with $BER_T = 10^{-3}$ and low-correlated channel ($\rho = 0.3$)

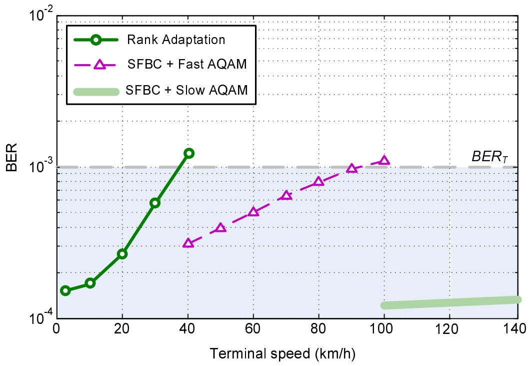
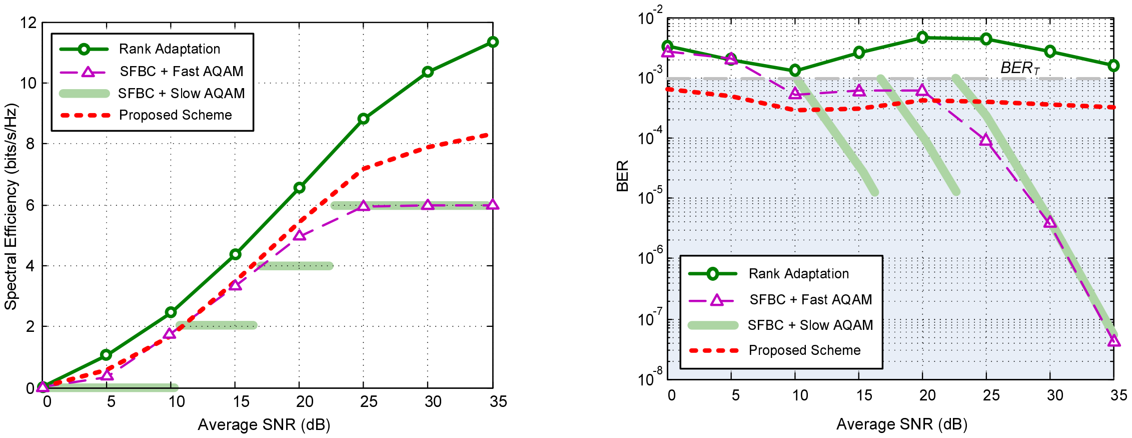


Fig. 6. Average BER as a function of user mobility with $BER_T = 10^{-3}$ and low-correlated channel ($\rho = 0.3$); average SNR $\bar{\gamma} = 20$ dB



(a) ASE performance

(b) Average BER performance

Fig. 7. Performance of the proposed link adaptation scheme in a variable user speed scenario with $BER_T = 10^{-3}$ and low-correlated channel ($\rho = 0.3$)

is only fulfilled in a low mobility scenenario, as shown in Fig. 6. In a moderate mobility scenario (from 40 to 90 kmh), the *SFBC + fast AQAM* mode should be applied in order to fulfill the QoS requirement, at the expense of a certain ASE degradation. For a high user speed (from 100 kmh on), *SFBC + slow AQAM* is the only mode that guarantees the QoS.

B. Proposed Link Adaptation

The proposed link adaptation algorithm has been evaluated in a variable speed scenario. That is, a user moving at a variable speed is considered in a typical suburban scenario [11]. We consider the user speed to be uniformly distributed within three speed intervals: from 10 to 40 kmh during 45% of the simulated time, from 40 to 90 kmh during 35% of time, and from 90 to 140 kmh for the 20% of time.

Fig. 7a and Fig. 7b show the ASE and BER performance for the proposed link adaptation scheme in the defined variable speed scenario. The ASE and BER performance of the three standalone transmission modes is also presented in the figures to facilitate a comparison. It can be seen in Fig. 7a that the *Rank Adaptation* mode outperforms the proposed link adaptation scheme in terms of ASE. However, the BER_T requirement is unfulfilled when Rank Adaptation is applied as a standalone mode, as shown in Fig. 7b. This is due to the performance degradation that takes place for this mode when the user speed is high. Thus, in comparison with the standalone modes, the proposed link adaptation scheme achieves the maximum ASE while the QoS requirement is fulfilled.

V. CONCLUSION

In this paper, we propose a new suboptimal algorithm for link adaptation in a MIMO-OFDMA cellular system under realistic conditions. Spatial correlation and imperfect CSI due to user mobility are considered. Modulation order and MIMO transmission mode are jointly selected in order to maximize the ASE while fulfilling a predefined QoS requirement. A performance evaluation of the proposed algorithm is provided under an LTE downlink scenario and a substantial ASE gain is observed in contrast to standalone transmission modes.

ACKNOWLEDGMENT

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