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Adaptive MIMO OFDMA for Future Generation Cellular Systems in a Realistic Outdoor Environment

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Abstract—This paper presents a downlink performance evaluation of a candidate physical layer for future generation cellular communications systems employing link adaptive MIMO-OFDMA. Adaptation between various modulation and coding schemes in combination with both space-time block codes (STBC) and spatial multiplexing (SM) on the basis of channel knowledge is considered. By means of ray-tracing software, a detailed example coherent time-variant channel trace is generated. Subsequent application of physical layer simulation software to this channel trace yields PER and throughput results for all available link adaptation parameters. Various channel parameters are considered against this data and the SNR and H matrix determinant are found to have the most significant influences on the system throughput. Subsequently, LA algorithms are proposed whereby the system adapts according to SNR only and both SNR and H matrix determinant. The performance of these algorithms is compared to the optimal case.

I. INTRODUCTION

To support an ever-increasing number of new services and to develop existing standards, research of future generation cellular systems has focused on providing higher data rates with increased spectral efficiency and improving coverage and communication reliability. A MIMO OFDMA system is very promising [1] and its performance can be further enhanced if a link adaptation (LA) algorithm [1,2] is adopted. In the absence of multiple antennas, Adaptive Modulation and Coding (AMC) schemes allow different data rates to be assigned to each user in the system depending on their channel conditions. In the case of a MIMO system, the adaptation can be further extended to switch between Space-Time Block Codes (STBCs) for diversity gain and spatial multiplexing (SM) for increased transmission rates [1, 2, 3]. The best choice of transmission parameters will vary according to the application requirements and channel conditions. This paper focuses primarily on the case of delay insensitive applications for which maximisation of throughput is the criterion for adaptation.

For LA, many papers have assumed instantaneous SNR feedback available at the transmitters. In [2] the authors suggested LA schemes based on averaging the space-time matrix and using a statistical channel model. However, feedback delay and system implementation complexity can limit the system performance in reality. This paper examines the performance of an adaptive MIMO OFDMA system in a realistic outdoor environment, modeled using ray tracing software. The throughput performance for the case of optimal LA and PHY mode selection is first presented, followed by the analysis of a realistic sub-optimal LA algorithm. This paper

presents the system performance when the choice of PHY mode is based on SNR only and on both SNR and H matrix determinant.

The remainder of the paper is organized as follows. Section II describes the PHY model and parameters, use of the ray tracing tool and the proposed LA algorithms. Section III presents comparative analysis of the adaptive system using optimum and sub-optimum LA algorithms based either on SNR only or both SNR and H matrix determinant. Section IV concludes the paper.

II. PHY AND CHANNEL MODELS

A. PHY Model and MIMO Schemes

The total bandwidth of an OFDM system is divided into a series of sub-carriers, and each sub-carrier is subject to a flat fading narrowband channel. With proper coding and interleaving across frequencies, OFDM exploits frequency selectivity to its advantage as a source of diversity. For an OFDMA scheme, all usable sub-carriers are grouped into multiple sub-channels which are then allocated to different users for data transmission. The key parameters, which are used in the simulation of the MIMO OFDMA system presented are the same as those in [4] and are shown in Table 1. The OFDMA system proposed in this paper is able to support up to 16 users simultaneously, and each user can be allocated to 48 sub-carriers. For this work, only one user is considered and hence the analysis equally applies to an OFDM system.

Table 1 Parameters for OFDMA system

Operating Frequency	5 GHz
Bandwidth	100 MHz
FFT Size	1024
Useful Sub-carriers	768
Guard Interval Length	176
Sub-carrier Spacing	97.656 KHz
Useful Symbol Duration	10.24 μ s
Total Symbol Duration	12.00 μ s
Channel Coding	Punctured 1/2 rate convolutional code, constraint length 7, {133,171} <i>total</i>
Number of Users	16

STBC and SM can be applied to an OFDMA system on a sub-carrier-by-sub-carrier basis. In this paper a 2x2 architecture has been adopted and SM employs a linear MMSE detection scheme. In an OFDM system, a group of N_f low rate data streams are transmitted instead of a single high rate data stream. Theoretically, the normalized channel capacity of a MIMO OFDM system is given as [7]:

$$C = \frac{1}{N_f} \sum_{f=1}^{N_f} \log_2 \left(\det \left(I_{N_R} + \frac{\rho}{N_T} H(f) H(f)^H \right) \right) \quad (1)$$

$$= \frac{1}{N_f} \sum_{f=1}^{N_f} \sum_{n=1}^N \log_2 \left(1 + \frac{\rho}{N_T} \lambda_n \right)$$

where f is the number of sub-carrier, ρ is the average SNR, N_T , N_R is the number of transmit and receive antennas respectively, N is $\min(N_T, N_R)$, λ is the eigenvalue of HH^H , and $(\cdot)^H$ denotes the Hermitian function. The determinant of the channel H matrix (independent of the received signal-to-noise ratio (SNR)), is given by $\det(H(f)H(f)^H)$ [10].

B. Channel Model

The proposed system is evaluated using 2-transmit, 2-receive antenna MIMO channel data from deterministic (ray traced) channel models. The deterministic model uses a site-specific multi-element ray tracing model that is capable of supporting a wide range of propagation mechanisms [8]. The outdoor ray tracing trial consists of a base station located on a building top (23m above ground level), and a grid of possible mobile station locations covering an area of 400mx400m (1.7m above ground). The base station uses 2 patch elements (20 λ spacing). The mobile station uses 2 monopole elements (0.6 λ spacing).

The system is also simulated using a statistical channel model, and the performance result is used as a reference for the system operating in a realistic urban environment. The statistical model [9] represents a typical large environment for NLOS conditions and 250ns average rms delay spread. The statistical channel model assumes uncorrelated MIMO channels.

C. Adaptive MIMO OFDMA

For the system considered in this paper, there are 6 AMC options [4], as shown in table 2. A simple approximation of the link throughput when ARQ is employed is given by: Data Throughput = $R(1-\text{PER})$, where R and PER are maximum data rate and packet error rate respectively for a given PHY mode.

Table 2 Transmission Modes and Data Rates

Mode	Modulation	Coding Rate	Coded Bits (subcarrier)	Max. Data Rate (R) Mbps (STBC / SM)
1	BPSK	$\frac{1}{2}$	1	32 / 64
2	QPSK	$\frac{1}{2}$	2	64 / 128
3	QPSK	$\frac{3}{4}$	2	96 / 192
4	16 QAM	$\frac{1}{2}$	4	128 / 256
5	16QAM	$\frac{3}{4}$	4	192 / 384
6	64 QAM	$\frac{3}{4}$	6	288 / 576

If exact prior knowledge of PER is available at the transmitter for all transmission modes for the current channel, optimal link adaptation can be achieved. However, since this is not possible in reality, an algorithm capable of achieving near-optimal mode selection given only (possibly limited) channel

knowledge is desired. The propagation modelling employed offers a highly flexible method of evaluating channel parameters in detail. In this paper, received SNR, H matrix determinant, rms delay spread, K factor and theoretical channel capacity (calculated using equation (1)) are all considered in terms of their usefulness for LA purposes. Simulation results show that the received SNR and the H matrix determinant particularly affect the system throughput. In the following section, the performance of a system adapted to the received SNR or received SNR and H matrix determinant are examined.

III. PHY PERFORMANCE ANALYSIS

Using the ray tracing model, complex MIMO channel impulse response data is derived on a point-to-multipoint basis for the entire area under consideration. From this data, the received SNR, H matrix determinant, rms delay spread, K -factor and theoretical capacity are determined for the entire area. The result for SNR is illustrated in Fig 1. By combining the channel data with a baseband PHY simulation tool, PER and throughput across the environment can also be determined.

In order to test the LA algorithms, a predetermined route (marked in grey in Fig 1) is investigated with high (1m) spatial resolution. The route is selected in order to represent a wide variety of the channel conditions seen in the overall environment.

A. Optimal Link Adaptation

Given knowledge of PER as a function of location, the throughput achieved by an optimal LA algorithm can be determined. Fig 2 shows this optimal throughput for the system and route considered, as well as for the cases of the same system with STBC only and SM only. The corresponding variations of the channel statistics along the selected path are also shown in fig. 2 for comparison and insight into their effects on throughput.

Starting from location A near the transmitter, both determinant and SNR values are high, which results in high throughput for both SM and STBC systems (Note: power control could also be exploited in this case).

As the path moves from B to C, the system reaches an area where MIMO sub-channels become more correlated, which reduces the amount of spatial diversity that can be utilized. Although in fig 2(d) a decline in the theoretical normalized capacity is shown, the throughput of both MIMO systems remain high due to the strong received SNR and moderately high rms delay spread offering frequency diversity, which can be exploited by the coded OFDM system without suffering ISI due to the use of a suitable guard interval.

The received SNR starts to drop as the receiver moves from C to D. In this region, there are many locations where correlation between antennas is high. This has significant impact on SM transmission. In addition, the variation of rms delay spread in this region is relatively low, so the data throughput is mainly dependent on the determinant. Therefore, the throughput of the SM system fluctuates as frequently as the channel determinant value. The requirement to maximize

throughput results in frequent switching between SM and STBC. An example of the system performance, in terms of PER versus SNR for a specific location in this region, is shown in fig. 3. At this location, the MIMO channels are highly correlated (H matrix determinant is only 0.028). This results in serious degradation in the PER performance of the SM system compared to that of STBC system, requiring approximately 25dB more SNR. This difference in PER between the two systems becomes more severe for higher modes. For mode 6, the SM is not able to operate until the SNR level reaches 40dB. Since the received SNR at this location is only 17.5dB, an STBC mode will be optimal in terms of throughput.

As the receiver keeps moving down to the far end of the path, the received SNR drops substantially to only a few dB. Here, SM fails to operate and STBC again offers superior throughput because it is comparatively insensitive to the high correlation and can achieve good throughput even with low received SNR.

B. Sub-Optimal Link Adaptation Algorithm

Although SM mode 6 offers the highest maximum data rate among all the proposed modes, high SNR can potentially support higher data rate modes which are not considered in this paper. On the selected route, there are many locations having high SNR, and mode selection at these locations is straightforward. Therefore, simulation results for the region from points C to E are more useful to study quantitatively since these are much more challenging for the Link Adaptation process.

Case 1: Link Adaptation based only on the Received SNR

In order to examine the possibility of using the received SNR as the sole parameter for LA, average PER and link throughput results can be used as a reference to perform link adaptation. Reference link throughput graphs are employed for the case of the statistical channel model detailed in section II part B for the cases of STBC and SM.

On the basis of knowledge only of the received SNR, a prediction of the PHY mode with the highest throughput for that SNR can be obtained via a look-up mechanism. Note that in this case the prediction is on the basis of a statistical average channel model rather than any detailed knowledge of the channel and that the statistical model is essentially arbitrary and has not been optimized to the overall environment or route. It should also be noted that AMC modes 1, 2 and 3 never offer the best throughput when in combination with SM for any channel conditions. Fig. 4 compares the throughput of this LA algorithm with the optimum. The correct mode is chosen **84.0%** of the time. The cause of the reduced throughput relative to the optimum in some locations can be analyzed by considering the SM-only and STBC-only cases. For STBC-only the correct mode is chosen in 98.6% of locations. For SM-only, the correct mode is chosen in 65.6% of locations. The result demonstrates that most mode selection errors occur in the SM case. This is expected since SM is more sensitive to the channel characteristics neglected by the SNR-only approach.

Case 2: Link Adaptation based on the Received SNR and the H Matrix Determinant

Since the MIMO channels of the ideal statistical model are perfectly uncorrelated, the H matrix determinant across all channel realizations has an average value of 2. In the realistic environment used in this paper, due to the limitation of spacing between antennas at BS and MS and angular spread, etc, the H matrix determinant (with approximate average value of 1) is much lower than the ideal value and varies from point to point as shown in fig. 2(b). As shown, when using SM, the system becomes more sensitive to the correlation level in the MIMO channels as the received SNR decreases. An improvement in system throughput is expected if the system is adaptive to both the received SNR and H matrix determinant.

The simulation results in Fig. 2 suggest that both the received SNR and H matrix determinant have significant impact on the performance of SM modes. In contrast, the received SNR is the dominant factor influencing STBC throughput. As discussed above, locations with very low H matrix determinant severely impair SM modes irrespective of SNR. Further consideration of Fig. 2 also suggests that in locations with moderately low determinant, SM modes typically achieve somewhat lower throughput than that suggested by the performance analysis for the statistical model and that SM mode 6 is only viable for determinants greater than 2.

Based on the simple SNR-lookup LA algorithm and the observations above, the LA algorithm described in Table 3 modifies the choice of mode via the SNR-lookup according to the level of the H matrix determinant. Note that the H matrix determinant only affects the choice of SM modes; when the SNR-lookup process indicates an STBC mode, that choice is unmodified.

Table 3 SNR and H Matrix Determinant based Link Adaptation Algorithm

$\det(H(f)H(f)^H)$	Action		
<0.1	SNR look up table, STBC only		
0.1—Threshold Level	SNR look up table	STBC	No change
		SM	Reduce mode to the next lowest throughput
Threshold Level—2	SNR look up table, SM mode 6 cannot be used		
>2	SNR look up table		

The throughput comparison between the optimum and the received SNR and H matrix determinant with a threshold level at 0.5 is shown in fig. 4. The results show that using this approach the optimal mode is chosen at **92.2%** of locations. This is a significant improvement and shows that this algorithm is able to perform very close to the optimum in terms of maximizing total system throughput most of the time.

For real time applications, it is desirable to constrain delay. Typically this requires control of the PER to levels below that which may be acceptable if only maximizing throughput. Since high PER most commonly results from selecting a high throughput mode when the MIMO channel is correlated, PER can be constrained by adjusting the threshold level of the H matrix determinant at step 3 of the algorithm to meet the requirement of a specific application. If the threshold level is

increased, the likelihood of severe PER is decreased as shown in fig. 5. However, the algorithm may become less sensitive to the frequent adjacent mode changes seen in the optimal case. The effect of the H matrix determinant threshold on system throughput can be illustrated more completely in a statistical way. The throughput error can be obtained by calculating the absolute difference in throughput between the optimum and sub-optimum cases. The CDF, showing the probability of operating below a certain throughput error level across the route from C to E, is plotted in fig. 6 (note the discontinuous vertical axis). The received SNR based system (equivalent to an H matrix determinant threshold level of 0) exhibits the worst performance. When adapting on the basis of both received SNR and H matrix determinant, the adaptive system with lower H matrix determinant threshold level is able to choose the correct low data rate mode for most of the time but makes more mistakes in choosing the mode with higher data rate, and vice versa. These results show that a suitable determinant threshold can reduce the worst case throughput errors by 100Mbps/s and ensure correct mode selection for over 15% more locations.

IV. CONCLUSIONS

The optimum adaptive system performance shows that, in most cases, highly correlated channels having a low H matrix determinant generally correspond to low rms delay spread and high K-factor, and vice versa. Unlike STBC, high correlation among MIMO channels can lead to undesirable performance and even error floors for SM systems. This is because SM systems rely on spatial diversity in the MIMO channels to recover transmitted messages. Received SNR is, unsurprisingly, another important parameter affecting system performance. For the SM system, high SNR is usually needed to compensate for the poor error performance compared to that of the STBC system, and achieve high throughputs with high operating modes. Therefore, for the adaptive MIMO OFDMA system, SM modes should only be adopted to achieve greater throughputs when the mobile terminal experiences relatively high received SNR and low correlated MIMO channels. On the other hand, STBC modes are usually adopted in areas which experience low received SNR or highly correlated channels. If the mobile terminals come to a region where no channel statistic is dominant, every factor plays a part in affecting the system throughput, and the system switches between STBC and SM mode based on various channel conditions.

Among all channel statistics, SNR has the most significant influence on the choice of PHY mode with H matrix determinant also has significant influence on the choice of SM modes. Driven by this observation, the possibility of having the system adapted to received SNR or SNR and the H matrix determinant has been examined and an effective LA algorithm proposed. For real time applications, excessive delays can be minimized by adjusting the H matrix determinant threshold.

Clearly, the analysis presented here is sensitive to the degrees of freedom provided by the PHY layer modes and to the specific environment chosen for simulation. Further work is required to consider other possibilities and investigate the adaptability of the determinant threshold further.

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Fig. 1 Received SNR with 30dBm Transmit Power

Fig. 2 Channel Statistics of the Selected Path with 30dBm transmit power: (a) SM/STBC/Adaptive MIMO Throughput (Mbps), (b) Determinant, (c) Received SNR (dB), (d) Capacity (bits/s/Hz), (e) RMS Delay Spread (ns), (f) K-Factor vs. Location points respectively

Fig. 3 PER Comparison between STBC and SM system Performance (rms delay spread: 38.3ns, H matrix determinant: 0.028, K-factor: -1.8)

Fig. 4 Throughput Comparison between the Optimum and the Received and H Matrix Determinant (Threshold level 0.5) Based System

Fig. 5 Throughput Performance of the Received SNR or/and H Matrix Determinant Adaptive System with threshold level at 0.75 and 1 respectively

Fig. 6 CDF Probability of the Adaptive System Performance below Certain Throughput Error Level