MIMO Techniques for Green Radio Guaranteeing QoS

Marios Nicolaou, Congzheng Han, Kian Chung Beh, Simon Armour, and Angela Doufexi

Abstract: **Environmental issues and the need to reduce energy consumption for lowering operating costs have pushed power efficiency to become one of the major issues of current research in the field of wireless networks. This paper addresses a number of multiple input multiple output (MIMO) precoding and scheduling techniques across the PHY and MAC layers that can operate under a reduced link budget and collectively improve the transmit power efficiency of a base station, while maintaining the same levels of service. Different MIMO transmission and precoding schemes proposed for LTE, achieving varying degrees of multiuser diversity in both the time, frequency as well as the space domain, are examined. Several fairness-aware resource allocation algorithms are applied to the considered MIMO schemes and a detailed analysis of the tradeoffs between power efficiency and quality of service is presented. This paper explicitly examines the performance of a system serving real-time, VoIP traffic under different traffic loading conditions and transmit power levels. It is demonstrated that by use of efficient scheduling and resource allocation techniques significant savings in terms of consumed energy can be achieved, without compromising QoS.**

Index Terms: **Green radio, long term evolution (LTE), multiple input multiple output (MIMO), precoding.**

I. INTRODUCTION

There are currently 4 billion mobile phone users in the world. The energy consumption and carbon dioxide emission has become a major concern for wireless network industries as the number of mobile phone users increases. A typical 24-hour mobile phone network in the UK consumes approximately 40 MW, excluding the power consumed by the users' handsets [1]. The worldwide telecommunications industry is currently responsible for 183 million tones or 0.7 of the total carbon dioxide emissions, which are increasing at a rapid rate [2]. In addition, the high energy prices increase the operating cost of cellular systems. In order to develop more power efficient and environmentally friendly wireless networks, the core 5 research programme of mobile VCE is set to focus on the green radio concept. It aims to deliver high data rate services with a 100-fold reduction in power consumption over current wireless communication networks, thereby reducing CO_2 emissions and deployment and operating costs of equipment manufacturers, network operators, content providers, etc. without compromising the quality of service (QoS) of the end user.

Long term evolution (LTE) is a next major step in mobile radio communications, and will be introduced as Release 8 in the 3rd generation partnership project (3GPP) [3]. The new evolution aims to reduce packet delays, improve spectrum flexibility and further reduce the cost for operators and end users. Some of the targets of the standard include peak download rates of up to 326.4 Mbps for a 4×4 antenna configuration and 172.8 Mbps for a 2×2 antenna configuration for every 20 MHz of spectrum. In the uplink, a peak upload rate of 86.4 Mbps is expected. Instead of the fixed spectrum in the previous releases, LTE aims to support a scalable bandwidth from 1.25 MHz up to 20 MHz.

The objective of this paper is to investigate the capabilities of various multiple antenna transmission and precoding techniques in combination with exploitation of multiuser diversity in order to reduce the transmit power consumption. The use of multiple input multiple output (MIMO) transmission techniques can significantly improve the data rate, reliability or both. One popular MIMO technique is space-time block coding (STBC) which is able to achieve full transmit diversity and enable reliable communication. Thus, in LTE, an Alamouti [4], [5] based space-frequency block coding (SFBC) technique is proposed in the standard and will be considered in this paper. Another technique that is also proposed in the LTE standard is spatial multiplexing (SM). SM gain is accomplished by simultaneously sending different data streams over the same radio resource, which can dramatically increase throughput and bandwidth efficiency.

Recently, a number of closed-loop MIMO scheduling and precoding techniques have been proposed for LTE [6], that incorporate an improved interface between the physical (PHY) and the data link control (DLC) layers in order to provide increased support for on demand QoS [7]. In [8], a precoding method for a MIMO-OFDMA scheme has been proposed in accordance to the LTE standard [6]. This precoding method relies on the use of a known (by both base station and mobile) codebook of unitary matrices, which is determined offline, generated according to a Fourier basis, providing uniform coverage across a sector. The transmitter applies the unitary matrices from the pre-defined codebook to the transmitted signal and allocates resources based only on the effective signal to interference and noise ratio (SINR) feedback for each of the precoding matrices along with its corresponding index. By using a linear receiver to separate the MIMO spatial layers, spatial resources can be assigned to either one user for the single user MIMO (SU-MIMO) scheme or to multiple users for the multi-user MIMO (MU-MIMO) scheme. Multi-user diversity refers to the increase in overall multi-user capacity achieved via an opportunistic resource allocation strategy for which the scheduler assigns resources according to the users' instantaneous channel conditions in time, frequency or/and space domain [9]. Previous work [10] has shown the capabilities of SU-MIMO in achieving spatial multi-user diversity gain and spatial multiplexing gain. In a MU-MIMO system, an additional 'layer' multi-user diversity gain can be extracted. Feedback can be further reduced

Manuscript received October 1, 2009.

The authors wish to acknowledge the financial support of the Core 5 Green Radio Programme of Mobile VCE. Marios Nicolaou also wishes to thank Toshiba Research Europe Limited for its financial support.

The authors are with the Centre for Communications Research, Department of Electrical and Electronic Engineering, University of Bristol, UK, email: {M.Nicolaou, Bernice.Han}@bristol.ac.uk, kianchung@gmail.com, {Simon.Armour, A.Doufexi }@bristol.ac.uk.

1229-2370/10/$10.00 © 2010 KICS

by only requiring the effective SINR (ESINR) of the preferred pre-coding matrix and its corresponding index in the codebook from each user. The full and partial feedback based beam selection strategies are explained in Section III.

The power efficiency performances of different MIMO transmission and pre-coding techniques are considered with several proposed resource allocation algorithms. While the goal is to reduce the total transmit power consumption, the abilities of these MIMO schemes to maintain certain levels of spectral efficiency and fairness are also examined.

Finally, real time, voice over IP (VoIP) traffic is considered in this paper. VoIP traffic is characterised by stringent packet latency requirements and periodic packet arrivals during active periods. Long term throughput is not a major concern; however, adequate rate needs to be provided in order to complete the transmission of VoIP packets within a specified tolerable delay period.

By investigating and exploiting various precoding and scheduling strategies, the goal in this paper is evaluate the transmit power efficiency while maintaining the same QoS level. Note that the work presented in this paper focuses on minimising the transmit energy consumption. Besides transmit energy, the energy consumed by signalling and the hardware processes such as rectifying and cooling, DSP processing, AD/DA conversion, and power amplification are assumed to remain constant.

The remaining of this paper is organised as follows: Section II introduces the system and channel model parameters. Section III describes the considered MIMO transmission and precoding schemes. Section IV introduces several channel-aware resource scheduling algorithms for the considered MIMO schemes. Section V presents the theoretical analysis of the energy consumption required by different considered schemes to maintain certain spectral efficiency. Corresponding simulation results are presented in Section VI. Section VII discusses the implications of resource allocation to the BS energy consumption based on the analysis of preceding sections. Section VIII considers the performance of the proposed scheduling and precoding schemes in a VoIP traffic scenario and examines the implications on QoS of reduced transmit power. This paper concludes in Section IX.

II. SYSTEM, CHANNEL, AND TRAFFIC MODEL

A. System Model

The core of the LTE downlink radio is defined by the conventional orthogonal frequency division multiplexing (OFDM) with data transmitted over several parallel narrowband sub-carriers. The use of the narrowband sub-carriers in combination with a cyclic prefix makes OFDM transmission particularly robust to multipath fading inherent in radio propagation. Considering a multi-user scenario, the performance analysis is performed on the downlink of a 3GPP LTE orthogonal frequency division multiple access (OFDMA) system. The total system bandwidth is divided into sub-channels, denoted as physical resource blocks (PRBs), which are then allocated to different users for multiple access purposes. Note that a PRB has both frequency (180 KHz) and time (1 ms) dimensions, and is the smallest element of resource allocation assigned by the base station scheduler. The key parameters of the considered LTE OFDMA downlink system are given in Table 1. There are 50 PRBs in the 10 MHz system, each consisting of 12 adjacent sub-carriers. Instead of feeding back channel quality indicators (CQI) for all the sub-carriers, a single CQI (based on the average quality of the 12 grouped sub-carriers comprising the PRB) can be fed back for each PRB and is assumed to be perfectly known at the BS. Perfect channel estimation is also assumed. A 24 bits cyclic redundancy check (CRC) enables error detection at the receiver. With the adoption of opportunist scheduling, users will be scheduled on their peaks, resulting in a more uniform channel response, and sub-carriers will experience similar channel gains. Therefore, due to the insignificant gain of power control in the frequency domain and the increased computational complexity of dynamic allocation, equal power allocation is assumed throughout the simulations [11]. The simulation results presented here assume a single, unsectorised cell configuration. Inter cell effects are a topic for future investigation.

Table 1. Parameters for LTE OFDMA downlink.

Transmission bandwidth		10 MHz
Time slot/Sub-frame duration		0.5 ms/1 ms
Sub-carrier spacing		15 kHz
Sampling frequency		15.36 MHz (4×3.84 MHz)
FFT size		1024
Number of occupied sub-carriers		601
Number of OFDM symbols per time slot (Short/Long CP)		7/6
CP length(s/sample)	Short	(4.69/72)×6 (5.21/80)×1
	Long	(16.67/256)
BS Tx power		43 dBm (20 W)
Propagation model		SCM urban macro
Noise power		-104 dBm
User equipment noise figure		9 dB

Table 2. Parameters for LTE OFDMA downlink.

Mode	Modulation	Coding rate	Data bits per time slot (1×1), (2×2)	Bit rate (Mbps)
1	QPSK	1/2	4000/7600	8/15.2
2	QPSK	3/4	6000/11400	12/22.8
3	16QAM	1/2	8000/15200	16/30.4
4	16QAM	3/4	12000/22800	24/45.6
5	64QAM	1/2	12000/22800	24/45.6
6	64QAM	3/4	18000/34200	36/68.4

B. Channel Model

The channel model used in the simulations is the spatial channel model extension [12] (SCME) urban macro scenario, specified in 3GPP [13]. SCME provides a reduced variability tapped delay-line model which is well suited for link level as well as system level simulation. A low spatially correlated channel is assumed for all the users where 10 λ spacing at the BS is employed. 2000 independently and identically distributed (i.i.d.) channel realisations are considered in each simulation. Six modulation and coding schemes (MCS) levels are considered, as shown in Table 2. A 2×2 MIMO architecture is considered in this paper but the analysis is readily extendible to higher MIMO orders. Equal power is allocated to each transmit antenna.

III. DESCRIPTION OF INVESTIGATED SCHEMES

A. Full-Feedback Unitary Codebook Based Beamforming

Unitary codebook based beamforming has shown capabilities in achieving spatial multiuser diversity gain and spatial multiplexing gain [9]. Unitary codebook based beamforming suggests that a predefined set of antenna beams is used, which ensure a good sector coverage [7]. With considerably lower uplink feedback requirements than the conventional eigenbeamforming approach, the transmitter applies a predefined set of precoding matrices to the transmitted signal and selects the best user based on the feedback of ESINR indicating channel quality for each of the precoding matrices along with its corresponding index.

The pre-coder design relies on the Fourier basis. The resolution of these beams is dependent on the overall codebook size. The codebook E, consists of the unitary matrix set, i.e., $V_E = \{V_E^0 \cdots V_E^{(G-1)}\}$ where $V_E^{(g)} = \left[v_{E,0}^{(g)} \cdots v_{E,M-1}^{(g)}\right]$ is the gth precoding matrix, and $v_{E,m}^{(g)}$ is the mth precoding vector in the set. According to the Fourier basis,

$$v_{E,m}^{(g)} = \frac{1}{\sqrt{M}}\left[w_{0m}^{(g)} \cdots w_{(M-1)m}^{(g)}\right]^T,$$
$$w_{nm}^{(g)} = \exp\left\{j\frac{2\pi n}{M}\left(m + \frac{g}{G}\right)\right\}. \quad (1)$$

The same unitary matrix V_E^g is applied to all users across all the sub-carriers of the same PRB. Different matrices are used across different PRBs. The received signal after FFT and guard interval removal becomes (time index t is omitted):

$$Y_{k,s} = H_{k,s}V_E^g X_s + W_{k,s}$$
$$= U_{k,s}D_{k,s}\left(V_{k,s}\right)^H V_E^g X_s + W_{k,s} \quad (2)$$

where k denotes a user index, s denotes a sub-carrier index, $(\cdot)^H$ denotes the Hermitian function and $H_{k,s}$ is a matrix containing user k's frequency responses of the channels between M transmit and N receive antennas at sub-carrier s. $D_{k,s}$ is a diagonal matrix including all the singular values of $H_{k,s}$ and $U_{k,s}$ and $V_{k,s}$ are the unitary matrices obtained by applying singular value decomposition (SVD) to $H_{k,s}$. X_s denotes an $M \times 1$ matrix containing the transmit signals at sub-carrier s at the BS and $W_{k,s}$ represents the additive complex Gaussian noise with zero mean and variance $(\sigma_{k,s})^2$. If V_E^g is equal to V_k, the $V_k^H V_E^g$ term becomes an identity matrix and the user k is said to be in the true eigenbeamforming configuration. The system adopts a linear MMSE receiver, which has interference suppression capability. For a 2×2 MIMO system, the MIMO channels can be decomposed into 2 separate spatial layers. The received signal $Y_{k,s}$ is multiplied by the MMSE filter $G_{k,s}$:

$$G_{k,s} = \left((H_{k,s}V_E^g)^H(H_{k,s}V_E^g) + \text{SNR}^{-1}I\right)^{-1}(H_{k,s}V_E^g)^H. \quad (3)$$

For data stream q at sub-carrier s, the user k computes the ESINR:

$$\text{ESINR}_{k,s}^q = \frac{E_s}{|(A_{k,s})_{qq}|\,\sigma_{k,s}^2} - 1 \quad (4)$$

where $A_{k,s} = \left((H_{k,s}V_E^g)^H(H_{k,s}V_E^g) + \text{SNR}^{-1}I\right)^{-1}$. E_s denotes the average symbol energy and $(\cdot)_{qj}$ indicates the element located in row q and column j.

Depending on the spatial resource allocation process, unitary codebook based beamforming defines two modes of operation. In SU-MIMO OFDMA, users are selected according to their average across the spatial layers. Each user then occupies all spatial layers of a PRB realising spatial division multiplexing (SDM) in conjunction with frequency division multiple access (different users can be assigned across the different PRBs over the frequency domain). A potentially more efficient spectrum utilisation can be achieved via MU-MIMO, whereby the spatial dimension is exploited by incorporating the capability of allocating different spatial layers of the same PRB to different users. MU-MIMO, also known as spatial division multiple access (SDMA), is expected to achieve a greater overall system performance gain over SU-MIMO. In a full feedback scheme, the serving BS receives CQI information regarding the spatial layers from all unitary matrices, allowing an overall optimisation of the aggregate rate by selecting the matrix that achieves the overall highest spectral efficiency. Every user calculates the average data rate across all the sub-carriers in each PRB and sends it to the BS through the feedback channel.

In a SU-MIMO system, for PRB c, denoting the index of the starting sub-carrier by b and the finishing sub-carrier by a, the average rate of user k is given by [9]:

$$R_{k,c} = \frac{1}{a-b+1}\sum_{s=b}^{a}\sum_{q=1}^{N}\log_2\left(1 + \text{ESINR}_{k,s}^q\right). \quad (5)$$

The BS allocates each PRB to a user according to the selected resource allocation algorithm. For the MU-MIMO scheme, different spatial layers can be allocated to different users to realise an additional spatial multiuser diversity gain. However, this approach increases the feedback by the number of spatial layers (minimum number of transmit and receive antennas) compared to the SU-MIMO scheme. Based on the ESINR calculated from equation (4), the user k calculates the rate of each spatial layer q on a PRB basis [9]:

$$R_{k,c}^q = \frac{1}{a-b+1}\sum_{s=b}^{a}\log_2\left(1 + \text{ESINR}_{k,s}^q\right). \quad (6)$$

For every PRB, the BS allocates transmission resources on a per spatial layer basis.

B. Partial-Feedback Unitary Codebook Based Beamforming

Depending on the codebook size G, unitary codebook based beamforming imposes the additional feedback requirement of transmitting a total number of G CQI values along with the corresponding matrix index of each CQI. In order to reduce this uplink feedback overhead, partial feedback techniques have been proposed in [10], whereby each user feeds back CQI for only its preferred matrix. In [14], it was shown that partial feedback SU-MIMO techniques attain the same performance as full feedback schemes. The optimisation of MU-MIMO schemes under partial feedback conditions is more complex. However, in the referenced paper it has been shown that a large codebook does not always ensure higher throughput under partial feedback conditions, as it increases the probability of information outage events, for which no CQI is available at the BS for a given spatial/frequency resource on the selected precoding matrix. For MU-MIMO schemes, the degree to which the partial feedback approach converges to full feedback is dependent on the combination of the total number of users and the codebook size G. This paper adopts an adaptive beam selection strategy based on the defined codebook size for partial feedback for which maximum throughput is achieved. The subsequent section assumes a range of users from 1-25 and a fixed codebook size $G = 2$. Perfect feedback information is assumed in the simulation. However, in practice, the feedback information is quantised to reduce the amount of feedback overhead in the uplink [15], with very marginal performance degradation.

C. Space Frequency Block Codes

In the LTE standard, an Alamouti based SFBC technique is proposed. This transmit diversity based method does not provide a linearly increasing channel capacity as the number of transmit and receive element grows simultaneously. Only one data stream (or layer) is transmitted for 2 or even 4 antennas. For SFBC transmission, the symbols transmitted from the two antennas on each pair of adjacent subcarriers are defined as follows:

$$\begin{bmatrix} y^0_{(1)} & y^0_{(2)} \\ y^1_{(1)} & y^1_{(2)} \end{bmatrix} = \begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix} \quad (7)$$

where x_1 and x_2 are the transmitted signals from two consecutive sub-carriers and $y^{(p)}_{(s)}$ denotes the symbols transmitted from antenna port p on the sth subcarrier. Since SFBC is not considered in combination with multi-user diversity, no channel feedback is required for resource allocation purposes.

IV. RESOURCE SCHEDULING ALGORITHMS

A. Greedy Scheduling Algorithm

A greedy algorithm (GA) aims to maximise the overall system throughput. Each PRB is assigned to the strongest user. The drawback of the GA is that the scheduler always picks the user with the highest data rate and gives the system resources to statistically stronger users. The GA only guarantees fairness in the case of identically distributed BS-mobile user links over a long time. When there are significant discrepancies in SNRs, some users are scheduled more often than others. In practice, it is usually not desirable to maximise the overall system throughput, but to meet the QoS requirements of as many users as possible. By taking into consideration different QoS metrics, such as packet delay, packet timeout ratio, etc., or even factors that concern traffic management, e.g. premium service or traffic capping, a set of eligible users can be identified, for which preferential beams can be selected. In the case of SISO, the resource allocation is based on the channel gain, where the detailed description is well known and hence omitted here due to limited space [16].

B. Proportional Fair Algorithm

The proportional fair (PF) algorithm originally presented by Tse [9] for single carrier schemes has been introduced to guarantee greater throughput fairness amongst users with unequal channel strength statistiscs. In a simple GA, users close to the BS will consistenly have channel gains higher than users further away and therefore occupy all available resources. The PF algorithm atttempts to alleviate this problem, by assigning resources to a user k^* based on the ratio of the current data rate capabilitiy and the average throughput utilisation meausered over a weighted window of length t_c, i.e., $R_k(t)/W_k(t)$. The extension of PF scheduling to multicarrier, OFDM transmission has been examined in [18]. Two variations of the PF algorithm, returning different degrees of tradeoffs in terms of complexity and fairness are examined. The first scheme suggests that each subchannel c is assigned an independent scheduler. In this case, the average throughput $W_k(t+1)$ is updated after the assignment of each subchannel according to:

$$W_{k,c}(t+1) = \begin{cases} \left(1 - \frac{1}{t_c}\right) W_{k,c}(t) + \frac{1}{t_c} R_{k,c}(t), & k = k^* \\ \left(1 - \frac{1}{t_c}\right) W_{k,c}(t), & k \neq k^*. \end{cases} \quad (8)$$

A second scheme, whereby the average throughput metric $W_k(t+1)$ is updated after the assignment of all subchannels of an OFDM symbol is also considered. This scheme requires much less implementation complexity as it only requires one scheduler. However, a delay in converging to full throughput fairness is expected due to the suboptimal update process of the fairness metric.

V. THEORETICAL ANALYSIS

The benefits of multiuser diversity (MUD), whereby users are scheduled only on their strongest PRBs have been widely studied in literature e.g., [9], [16]. Provided that different users experience independent fading, the average system spectral efficiency can be increased as a function of the number of users. The precoding systems examined in this paper achieve varying degrees of MUD. It is therefore expected that for a given SNR, different schemes will achieve different spectral efficiency. To illustrate this, Fig. 1 presents system theoretical spectral efficiency results, calculated according to Shannon's capacity limit, for a range of SNR values for a total number of users, K=10, for the SISO, SFBC, and MIMO precoding schemes that were outlined in the previous section. The schemes that achieve the highest degree of MUD exploitation (time/frequency and space) e.g., MU-MIMO achieves the highest capacity for any given SNR value.

The energy consumption of multi-user SISO and various MIMO schemes are compared to the SFBC scheme using the energy consumption gain (ECG) metric [19]. ECG is defined as a comparison metric between the reference system and considered system. SFBC is chosen to be the reference system in this paper and E_{ref} corresponds to the received SNR required by a SFBC system to meet the average data rate target of 3 bits/s/Hz. E_{sys} corresponds to the received SNR requirement of each of the considered scheme to achieve the average data rate target.

$$\text{ECG} = \frac{E_{\text{ref}}}{E_{\text{sys}}} = \frac{E_{\text{SFBC}}}{E_{\text{sys}}}. \quad (9)$$

If ECG is greater than 1, the considered system consumes less

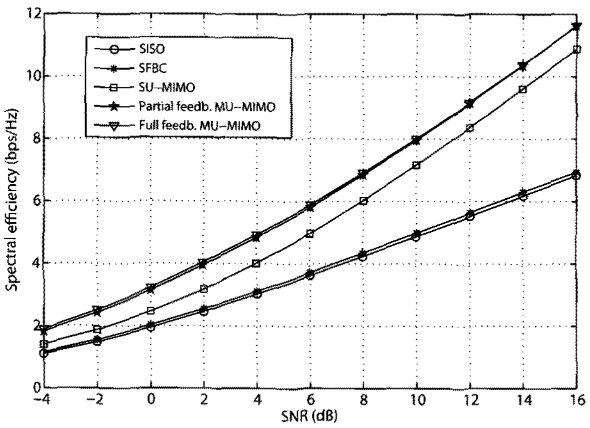


Fig. 1. Theoretical spectral efficiency for SISO and different precoding schemes for $K = 10$.

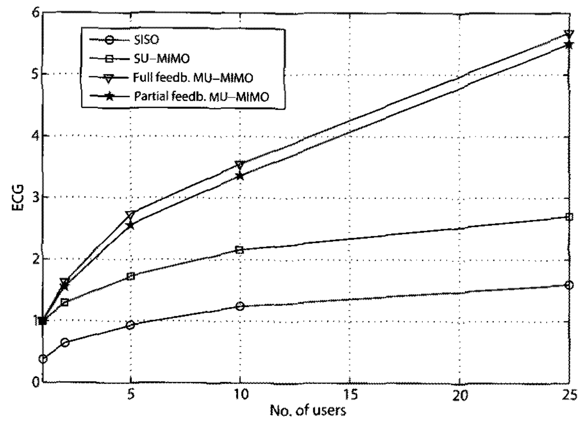


Fig. 2. Theoretical ECG of multi-user SISO and various MIMO schemes, relative to SFBC at 3 bits/s/Hz spectral efficiency.

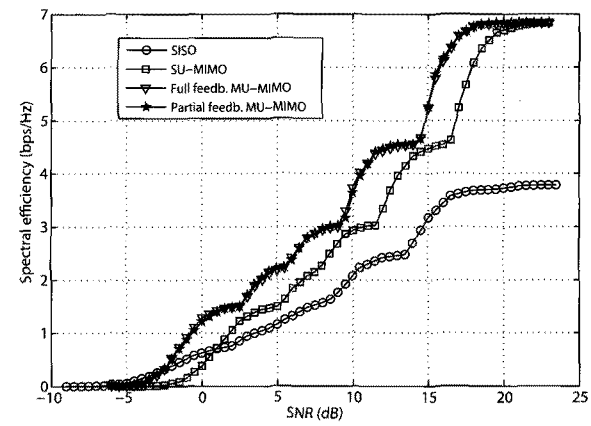


Fig. 3. Simulated spectral efficiency for SISO and different precoding schemes for $K = 10$.

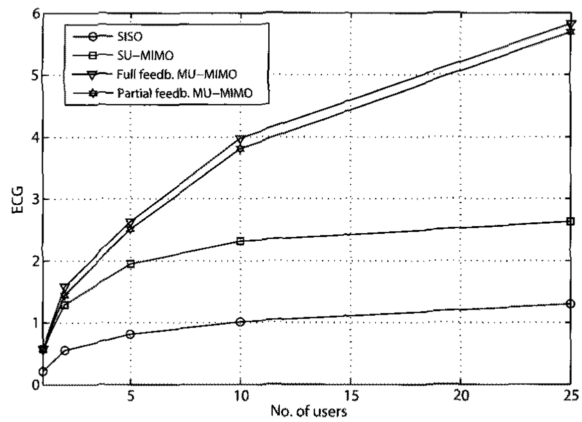


Fig. 4. Simulated ECG of multi-user SISO and various MIMO schemes, relative to SFBC at 3 bits/s/Hz spectral efficiency.

energy than the reference system. It is worth noting that resource allocation is not considered in the case of SFBC scheme. This is consistent to the proposed LTE standard where channel dependent scheduling is not applicable to the SFBC scheme [5].

Fig. 2 shows the theoretical ECG of multi-user SISO and various MIMO precoding schemes over SFBC, as a function of the number of users for maintaining a fixed overall system spectral efficiency of 3 bps/Hz, which is calculated from the average data rate across all considered users. The fixed spectral efficiency of 3 bits/s/Hz is an arbitrary metric chosen here for comparison purposes. It is expected that similar trends will occur for other spectral efficiencies, but with a change in the absolute energy consumption. A trend, whereby the performance gain increases as a function of the number of users is observed. The decrease in the energy consumption is significant when the MUD exploitation is considered, especially in the SISO case. A notable difference between schemes utilising the additional spatial diversity component and those who do not can also be observed. The exploitation of the additional spatial diversity enables a possible further reduction in energy consumption.

VI. SIMULATION RESULTS

Fig. 3 shows the simulated performance of overall system spectral efficiency of SISO scheme and different MIMO precoding schemes in the downlink of 3GPP LTE. The spectral efficiency is derived from the achievable average throughput of all the users given the transmission bandwidth. The achievable average throughput is given by, throughput $= R(1 - \mathrm{PER})$ where R and PER are the bit rate and the residual packet error rate for a specific mode respectively. The throughput envelope is obtained by using ideal adaptive modulation and coding (AMC) based on the (throughput) optimum switching point. Simulated results are very consistent with the theoretical results. The simulation results show that the spectral efficiency of MIMO precoding schemes significantly outperform the SISO scheme. Additionally, in line with the theoretical results, the additional spatial diversity of both the MU-MIMO schemes achieve a further performance gain of 2-3 dB compared to SU-MIMO.

Fig. 4 shows the simulated ECG of multiuser SISO and MIMO precoding schemes over SFBC, as a function of the number of users at a fixed overall system spectral efficiency of 3 bits/s/Hz. The simulated results match with the theoretical trend of Fig. 2. Fig. 4 shows that a significant energy reduction can be obtained by exploiting the MUD gain. This can be clearly observed in the SISO scenario, where in this case, the energy reduction comes solely from the MUD gain. Furthermore, additional energy reduction can be achieved by both the MU-MIMO schemes where additional spatial diversity is exploited. The use of precoding matrices can optimise the perceived gain in the re-

Table 3. Average and variance of the ECR for different precoding schemes.

	ECR(μ J/bits)	Variance
SISO	4.103	0.6923
SU-MIMO	1.708	0.0575
Full feedb. MU-MIMO	1.524	0.0285
Partial feedb. MU-MIMO	1.564	0.0312

Table 4. Average and variance of the ECR for SU-MIMO with different PF configurations.

	Per subchannel update		Per symbol update	
Window length(t_c)	ECR (μ J/bit)	Variance	ECR (μ J/bit)	Variance
300	2.836	0.0671	1.888	0.0401
1000	2.075	0.0361	1.736	0.0488
10000	1.931	0.0396	1.731	0.0493

Table 5. Average and variance of the ECR for MU-MIMO with different PF configurations.

	Per subchannel update		Per symbol update	
Window length(t_c)	ECR (μ J/bit)	Variance	ECR (μ J/bit)	Variance
300	1.801	0.0527	1.6434	0.0040
1000	1.550	0.0240	1.6433	0.0046
10000	1.546	0.0259	1.6256	0.0046

ceiver to achieve the additional gain, which can be translated to energy reduction at the transmitter. MU-MIMO achieves 5-fold reduction in energy consumption compared to SFBC. It has to be noted that results of Fig. 3 are specific to the specific scenario (K=10). In contrast to the theoretical simulation, granularities in the PHY mode selection and the different SNR ranges that arise from simulation modeling result in different modes being selected. This explains the deviation of the performance gains from theoretical to simulation results. It is worth noting, however, that by using AMC, the actual simulation results outperform theoretical expectations in the relative power reduction comparison.

VII. DISCUSSION

The power efficiency of a considered scheme can be represented by the energy consumption rate (ECR), which calculates the energy required per delivered information bit [20]:

$$\mathrm{ECR} = \sum_{k=1}^{K} \frac{(P_k T)}{(R_k T)} = \sum_{k=1}^{K} \frac{P_k}{R_k} \quad (J/bits) \tag{10}$$

where P and R are the average transmit power and data rate, respectively. T is the time index. The lower the ECR, the higher the power efficiency is. Analysis in Sections V and VI has shown that precoding schemes that harness the benefits of multiuser diversity to a higher degree require less transmit power from the BS to achieve the same throughput. It is thus expected that these schemes will have a lower ECR, which translates to improved power efficiency.

In Table 3, the ECR of different MIMO schemes and the corresponding variance over different channel realisations is presented, for the case of resource allocation via the GA. These results are in accordance with Figs. 2 and 4, showing that schemes

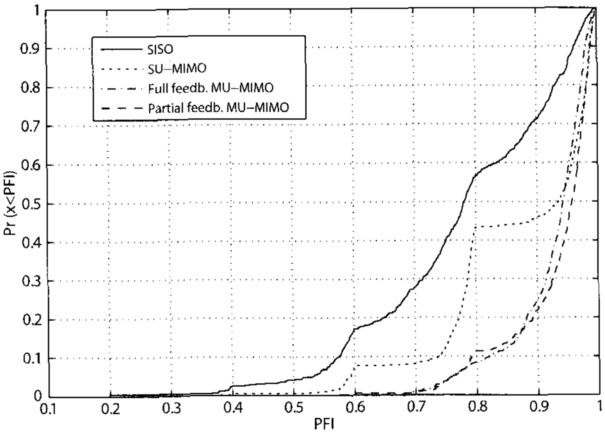


Fig. 5. Power fairness index for SISO and different precoding schemes.

employing a higher degree of diversity achieve the lowest cost in terms of energy for each information bit. It can also be observed that a more equally distributed ECR is obtained from the more power efficient schemes. Hence, a higher degree of multiuser diversity not only ensures an overall improvement in power efficiency but also improves the reliability of the energy cost estimation. This improved reliability can be attributed to the fact that deep fades occurring in wireless channels are effectively removed from the aggregate received channel signal at the BS [15]. Schemes exploiting the additional spatial layer for diversity generate a more flat aggregate channel response, resulting in fewer deep fades and hence in a more predictable channel response.

A trade-off is known to exist between power efficiency and power fairness, which is measured using a modified Jain's power fairness index (PFI) defined as [19]:

$$\mathrm{PFI} = \frac{\left(\sum_{k=1}^{K} \frac{P_k}{R_k}\right)^2}{K \sum_{k=1}^{K} \left(\frac{P_k}{R_k}\right)^2}. \tag{11}$$

The PFI provides an indication of how fairly power is allocated to different users with respect to their achieved rates. Fig. 5 shows the cumulative distribution functions of the PFI for different precoding schemes measured over a number of channel realisations, under the assumption of a maximum SNR scheduling approach. A small PFI indicates that the channel is underutilised, i.e., a fixed amount of power yields lower throughput, or equivalently, higher power is required to transmit a fixed amount of information. Schemes utilising the additional spatial layer, e.g., MU-MIMO (full feedback and partial feedback) achieves overall a higher power allocation fairness, with PFI values consistently closer to unity. Hence, schemes that efficiently exploit MUD not only reduce the average cost in terms of power for providing a fixed amount of information, but also ensure an overall fairness in terms of providing power to users in order to transmit a fixed amount of information. Analysis has concentrated in the downlink of the system. However, these results are consistent for the uplink as well, for which transmit power constraints from the mobile terminal makes the PFI metric much more relevant.

In Tables 4 and 5, we present the associated ECRs for full

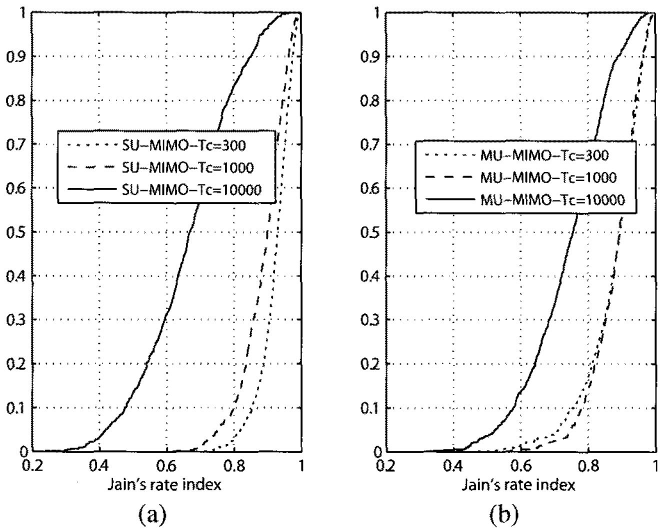


Fig. 6. Jain's rate fairness index for different window lengths: (a) SU-MIMO and (b) MU-MIMO.

feedback SU-MIMO and MU-MIMO respectively for different values of the fairness tuning parameter t_c, considering the two variations of the PF scheduling approach. The results show a direct relationship between the t_c and the ECR. The PF algorithm converges to GA for a large window length, as this decreases the dependency of the selection metric on previous utilisation. The rate fairness performance of different schemes can be measured using a modified Jain's rate fairness index (RFI) [21]:

$$\mathrm{RFI} = \frac{\left(\sum_{k=1}^{K} R_k\right)^2}{K\sum_{k=1}^{K}(R_k)^2}. \tag{12}$$

Fig. 6(a) and (b) consider the cumulative distribution function of the Jains's rate fairness index with regards to throughput for SU-MIMO and MU-MIMO, respectively. It can be seen that for configurations exploiting higher degrees of fairness, the corresponding Jain's rate fairness index is consistently closer to 1, showing high degrees of fairness. Higher induced throughput fairness arising from a low t_c value, however, results in suboptimal throughput improvements, since the probability of scheduling users on weak PRBs increases, due to the more uniform throughput distributions. Therefore, a tradeoff exists between power fairness and throughput fairness. Despite the obvious benefits of the PF in terms of ensuring throughput fairness, this suboptimal scheduling reflects on the energy cost required to transmit a given amount of information. By increasing t_c, the ECR converges to that of a GA approach. Decreasing t_c increases the associated throughput fairness but also results in increased power requirements per transmitted bit. Hence, it can be argued that in terms of power efficiency, a rate fairness-oriented scheduling approach results in sub-optimal performance, requiring higher transmit power levels to maintain a fixed level of service.

VIII. QoS PERFORMANCE

Previous sections in this paper have shown that a greedy scheduling approach not only improves aggregate throughput performance but can also reduce the power consumption required for providing a fixed amount of information. In [22], it has been shown that a greedy scheduling approach for VoIP traffic results in a higher call admittance capacity and reduced packet delays compared to fairness oriented algorithms. Additionally, since a simple rate maximisation scheduling approach assigns users on their strongest PRBs, higher modulation and lower coding rates can be tolerated, which consequently improves the spectral efficiency of the system, resulting in lower packet delays and lower packet loss rate (PLR). This section examines the performance of SU-MIMO and MU-MIMO techniques under two, transmit power levels (43 dBm and 40 dBm) for a varying codebook size.

Table 6. VoIP system configuration parameters.

Cell configuration	Single cell
Cell radius	800 m
MAC frame duration	5 ms
Tx. power	43 dBm, 40 dBm
Min. BS-MS distance	75 m
M. BS-MS distance	800 m
BS-MS distance distribution	Uniform
User no.	20-60
Codebook size	2/4/8

Table 7. VoIP traffic distribution parameters.

Component	Distribution	Parameters
Active state duration (ON)	Exponential	Mean=0.4 s
Inactive state duration (OFF)	Exponential	Mean=0.6 s
Packet inter-arrival rate within a burst	Fixed	r=5 packets/s

A. Channel Scenario

The physical configurations are summarised in Table 6. For simulation purposes, a dedicated band of 240 KHz is assigned solely for VoIP traffic. Resource allocation is performed on a per-subcarrier basis. It should be noted however that results are consistent and scalable for longer bandwidths and different PRB configurations. Similarly, the simulated network considers a single cell configuration with no sectorisation.

B. VoIP Traffic Model

A two state Markov process is used to model VoIP representing the active voice period and silence period respectively [23]. The alternating periods of activity and silence are exponentially distributed with average durations $1/\mu$ (μ is the parameter of the exponential law of the active period) and $1/\lambda$ respectively (λ is the parameter of the exponential law of the silent period). Therefore, the total fraction of time the voice source is active is $\lambda/(\mu+\lambda)$. Each VoIP session is either in the active or inactive state. During the active state, fixed sized packets of 32 bytes are generated at a constant interval of 20 ms.

Table 7 summarises the packet generation parameters and arrival/service distributions for VoIP traffic. The maximum tolerable packet delay for VoIP is set to 30 ms. The average packet timeout ratio is also a QoS factor. Excessive packet timeouts will considerably degrade the quality of received speech and should thus be kept low. The degree of tolerable packet timeouts is dependent on the specific codec. A packet scheduler op-

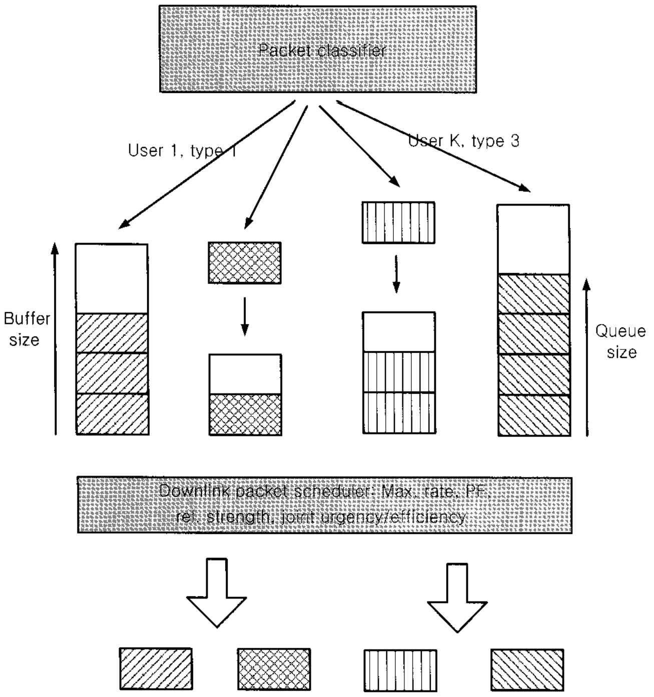


Fig. 7. Generalised packet scheduler structure.

erating at the MAC layer is the critical element for delivering QoS. Fig. 7 shows a generalised packet scheduler structure. The packet scheduling system at the BS consists of three blocks: A packet classifier (PC), a buffer management block (BMB), and a packet scheduler (PS). The packet classifier classifies incoming packets according to their types and QoS profiles, and forwards them to buffers in BMB. The BMB maintains QoS statistics such as the arrival time and the delay deadline of each packet, the number of packets, and the head-of-line (HOL) delay in each buffer. Finally, the PS transmits packets to users according to the scheduling priority.

QoS for VoIP traffic can be quantified in terms of the average packet delays experienced by each user during a session. Packets exceeding the maximum tolerable packet delay are assumed to timeout, and all information transmitted on that packet is lost. An ideal AMC scheme that maintains low packet error rates (PERs) [24] ($< 10^{-3}$) is adopted, in order to keep the number of packet re-transmission low. The aggregate packet loss rate (PLR) is therefore assumed to be dependent entirely on packet timeouts. The aggregate system's capability in providing service is defined by the maximum number of admitted users for which a certain percentage of QoS outage can be tolerated.

C. *Performance Analysis*

Fig. 8 shows the average packet delay experienced under different channel loading conditions for full feedback SU-MIMO and MU-MIMO for different codebook sizes, for a BS Tx. power=43 dBm. It can be seen that the packet delay is highly dependent on the amount of requested traffic, represented by the number of users with simultaneous VoIP sessions. By increasing the codebook size, the higher diversity is translated into higher throughput which allows packets to be served somewhat quicker. However, significant benefits arise from the MU-

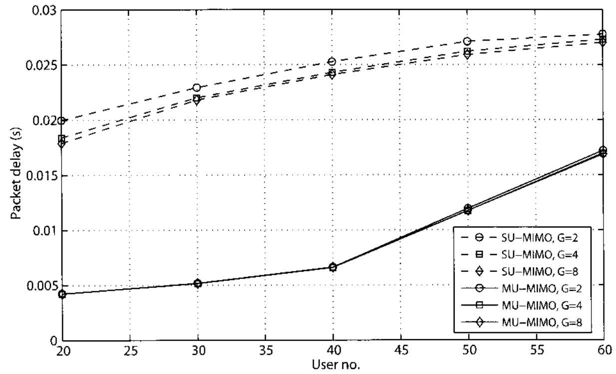


Fig. 8. Average VoIP packet delays for SU-MIMO and MU-MIMO, Tx. power 43 dBm.

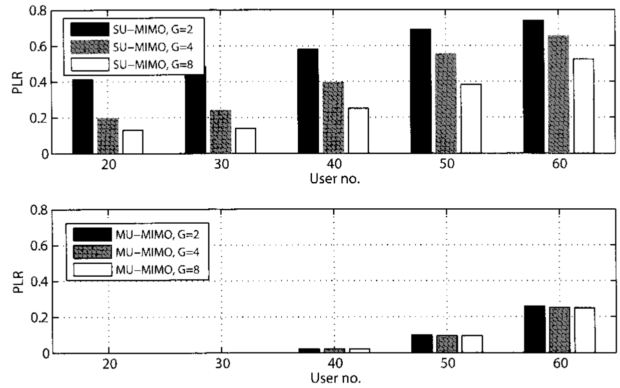


Fig. 9. Average VoIP packet loss ratios for SU-MIMO and MU-MIMO, Tx. power 43 dBm.

MIMO approach, where notable reductions in packet delay are observed. This reduction can be attributed both to the higher AMC levels exploited by MU-MIMO, as well as due to improved multiuser diversity. By effectively doubling the available resources, twice as many users can be simultaneously served, reducing the time packets remain in the buffer.

In Fig. 9, we show the associated PLRs for SU-MIMO and MU-MIMO. A correlation between packet delays and packet timeouts is observed. Overall, MU-MIMO experiences lower PLRs. Reducing the transmit power will inevitably result in performance degradation in any scheme due to the reduced link budgets which results in a lower mode being chosen in order to preserve required PER levels. This paper examines the effects of reducing the transmit power by 3 dB, i.e., halving the total transmit power.

Fig. 10 shows the corresponding average packet delays experienced for SU-MIMO and MU-MIMO (full feedback and partial feedback) for a codebook size, G=2, for a Tx. power = 40 dBm. Unsurprisingly, the average packet delays tend to increase, due to the lower link budgets achieved. Lower modulation and coding schemes are used which result in lower spectral efficiency and hence lower data rates can be realised by users.

Fig. 11 examines the average packet loss rate arising from the considered schemes. Comparing the findings with those of Fig. 9, it can be seen that the performance degradation due to reduced transmit power is minimal in the case of MU-MIMO techniques, whereby PLRs are very close to that of a BS with

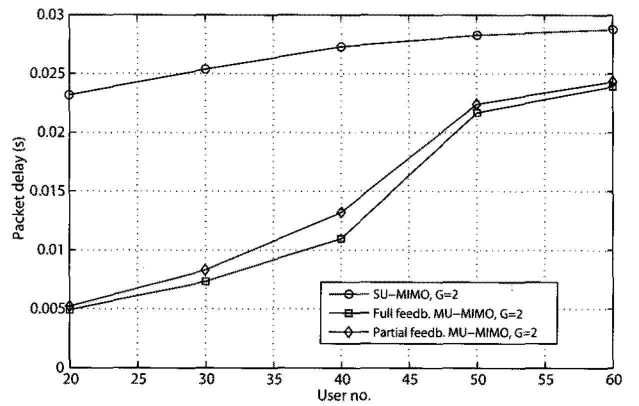


Fig. 10. Average VoIP packet delays for SU-MIMO and MU-MIMO schemes, G=2, Tx. power 40 dBm.

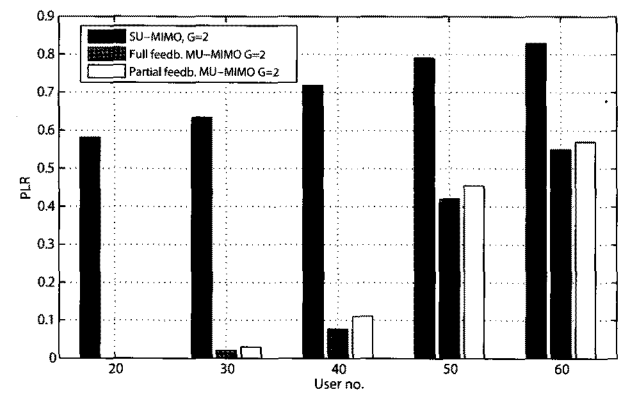


Fig. 11. Average VoIP packet loss ratios for SU-MIMO and MU-MIMO, Tx. power 40 dBm.

a transmit power 3 dB higher. It can be observed that even with reduced feedback, MU-MIMO still maintains higher QoS statistics than SU-MIMO, despite the 3 dB transmit power reduction. The results can be related to the ECG metric, for the requirement of achieving a target packet timeout for a specific number of users. By taking SU-MIMO as the reference scheme and MU-MIMO as the scheme under consideration, a 3 dB transmit power saving would translate to an ECG value of 2. These results show the huge potential of MU-MIMO as an approach towards the design of power efficient wireless systems. Through more efficient scheduling, enabled by the joint exploitation of temporal, spectral as well as spatial dimensions transmit power requirements can be eased, whilst not compromising the perceived service quality of the end user.

IX. CONCLUSION

The concept of green radio is to develop more environmentally friendly, low-power and energy efficient solutions for future wireless networks. This paper investigates the power efficiency of a number of MIMO transmission and precoding techniques, SFBC, SU-MIMO, and MU-MIMO under full and partial feedback conditions in combination with resource allocation strategies exploiting multiuser diversity. The analysis is performed on the downlink of a 3GPP LTE OFDMA system and both theoretical and simulation performances are presented. A detailed consideration of feedback overhead of different MIMO schemes is presented. In addition, the power efficiency of the overall system and individual users are also discussed and compared for different MIMO precoding strategies and resource allocation algorithms. For the proposed LTE system, if no multi-user diversity is considered, SFBC is a feedback free MIMO transmission scheme and achieves significant power savings over a SISO system. However, since it does not offer any data rate improvements, the savings on cost per bit is still limited. The capabilities of the examined MIMO precoding strategies to exploit multiuser diversity in time, frequency and space domain vary. All MIMO schemes benefit from multiuser diversity and show improved power efficiency as the number of users increases. The MU-MIMO is the most power efficient and fair schemes as a result of an additional layer spatial multiuser diversity gain, although it have a larger feedback overhead. The feedback can be reduced by adopting a partial feedback strategy for beam selection to achieve a sub-optimal performance. A proportional fair scheduling approach has shown suboptimal results in terms of power savings. This has been attributed to the fact that resources are scheduled on suboptimal resources that require a higher SNR to achieve a fixed data rate. A greedy, rate maximisation approach has not only shown improved power efficiency, due to the more efficiency exploitation of diversity, but also a higher power fairness allocation, by allocating roughly the same power to each user for the transmission of a fixed amount of data. The improved power fairness allocation, however, comes at the expense of lower throughput fairness and hence an optimum tradeoff given specific requirements needs to be determined.

The considered MIMO precoding schemes have been tested in a realistic channel and traffic model scenario. A real time, VoIP traffic scenario has been introduced in order to examine the QoS capabilities of each precoding scheme. An ideal AMC scheme has been assumed, designed to maintain the number of packet re-transmissions low. MU-MIMO has shown improved resilience to lower link budgets while preserving QoS levels. This resilience allows for a reduction in the transmit power from the BS. This paper has demonstrated that a 3 dB reduction in power has minimal effect on QoS, provided that efficient scheduling and resource allocation process. These results show the great potential of MU-MIMO techniques in reducing transmit power consumptions, in line with the targets of the green radio research programme (core 5) of mobile VCE.

REFERENCES

[1] Mobile VCE Core-5 Research Area, "Green radio infosheet," [Online]. Available: http://www.mobilevce.com/frames.htm?core5research.htm

[2] IDATE News 453, "Green telecom-calling for a better future," 5 Jan. 2009, [Online]. Available: http://www.idate.fr/pages/index.php?rubrique =etude&idr =16&idp=334&idl=7

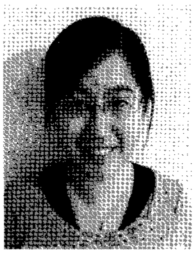
[3] 3GPP, "3GPP; Technical specification group radio access network; (E-UTRA) and (E-UTRAN); Overall description; Stage 2 (release 8)," 3GPP TS 36.300 V8.8.0, Mar. 2009, [Online]. Available: http://www.3gpp.org/ ftp/ Specs/html-info/36300.htm

[4] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas. Commun.*, Vol. 16, No. 8, pp. 1451–1458, 1998.

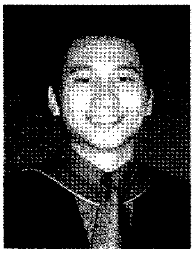
[5] E. Dahlman, S. Parkvall, J. Skold, and P. Beming, "3G evolution: HSPA and LTE for mobile broadband," *Academic Press*, 2008.

[6] 3GPP, "Multiple input multiple output (MIMO) antennae in UTRA (Release 7)," TR 25.876, 2007.
[7] H. Rohling and R. Grunheid, "Cross layer considerations for an adaptive OFDM-based wireless communication system," *Wirel. Pers. Commun.*, vol. 32 pp. 43–57, 2005.
[8] Samsung, "Downlink MIMO for EUTRA," *3GPP-TSG RAN WG1*, Meeting#43, R1-051353.
[9] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Trans. Info. Theory*, vol. 48, pp. 1277–1294, 2002.
[10] K. C. Beh, C. Han, M. Nicolaou, S. Armour, and A. Doufexi, "Power efficient MIMO techniques for 3GPP LTE and beyond," in *Proc. IEEE VTC Fall*, Anchorage, Alaska, USA, Sept. 2009.
[11] J. Jang and K. Bok Lee, "Transmit power adaptation for multiuser OFDM systems," *IEEE J. Sel. Areas Commun.*, Vol. 21, No. 2, pp. 171–178, Feb. 2003.
[12] D. S. Baum, J. Hansen, and J. Salo, "An interim channel model for beyond-3G systems: extending the 3GPP spatial channel model (SCM)," in *Proc. IEEE VTC Spring*, 2005.
[13] 3GPP TR 25.996 V6.1.0, "Spatial channel model for MIMO simulations," [Online]. Available: http://www.3gpp.opg.ftp/Specs/html-info/25996.htm
[14] M. Nicolaou, A. Doufexi, and S. Armour, "Performance analysis for partial feedback downlink MIMO with unitary codebook beamforming for LTE," in *Proc. IEEE ICC*, Dresden, Germany, 2009.
[15] S. Sesia, I. Toufik, and M. Baker, "LTE: The UMTS long term evolution: From theory to practise," *John Wiley and Sons*, 2009, pp. 207–239.
[16] Y. Peng, S. Armour, and J. McGeehan, "An investigation of dynamic subcarrier allocation in MIMO-OFDMA systems," *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 2990–3005, Sept. 2007.
[17] Y. Liu and E. Knightly, "Opportunistic fair scheduling over multiple wireless channels," in *Proc. IEEE INFOCOM*, 2003.
[18] H. Wang, L. Xiao, S. Zhou, X. Xu, and Y. Yao, "Dynamic resource management in the fourth generation wireless systems," in *Proc. ICCT*, 2003.
[19] B. Badic, T. O'Farrell, P. Loskot, and J. He, "Energy efficient radio access architectures for green radio: Large versus small cell size deployment," in *Proc. IEEE VTC Fall*, Sept. 2009.
[20] R. Wang, J. S. Thompson, and H. Haas, "A new framework for designing power-efficient resource allocation under rate constraints," in *Proc. IEEE VTC Fall*, Sept. 2009.
[21] R. Jain, D. Chiu, and W. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared computer system," *DEC Research Report TR-301*, Digital Equipment Corporation, Sept. 1984.
[22] M. Nicolaou, A. Doufexi, S. Armour, and Y. Sun, "Simple transmit diversity technique for wireless communications," in *Proc. IEEE VTC Fall*, 2009.
[23] H. Hassan, J. M. Garcia, and C. Bockstal,, "Aggregate traffic models for VoIP applications," in *Proc. ICDT*, 2006.
[24] O. Awoniyi and F. A. Tobagi, "Effect of fading on the performance of VOIP in IEEE 802.11 a WLANs," in *Proc. IEEE ICC*, 2004.

Marios Nicolaou received a M.Eng. degree in Electronic and Communications Engineering from the University of York, UK, in 2006. From 2006, he has been working towards his Ph.D. at the University of Bristol, UK, at the Centre of Communications Research (CCR) in the field of Next Generation Wireless Networks, in collaboration with Toshiba Research Labs Europe. His major interests include MIMO, OFDMA, opportunistic scheduling, adaptive resource allocation and link adaptation, QoS guarantees, and green radio.

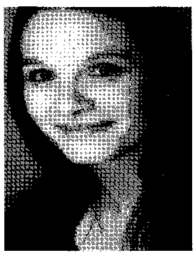


Congzheng Han received her B.Eng. and Ph.D. degrees in Electronic and Communications Engineering from the University of Bristol, UK in 2004 and 2008, respectively. She was awarded the Dorothy Hodgkin Postgraduate Awards. She is currently a member of research staff in the Centre for Communications Research at the University of Bristol and is contributing to the ViewNet UK TSB project and the Mobile VCE's Green Radio project. Her research interests include wireless LANs, future generation standards (LTE), multi-carrier modulation techniques, multiple antenna systems, multiple access, radio resource management, opportunistic scheduling, location-aided communications, cross-layer design, power efficient communications, and multimedia transmission.



Kian Chung Beh received his B.Eng. degree from Faculty of Engineering, Multimedia University (Cyberjaya, Malaysia) in 2003. After his first degree, he worked in Motorola as firmware development engineer before he continued his postgraduate studies. He completed his M.Sc. and Ph.D. in University of Bristol in year 2005 and 2010, respectively. His research areas lie on the future wireless/mobile communications with emphasis on cross layer optimization, hybrid ARQ, resource allocation, and scheduling.

Simon Armour has been an academic at the University of Bristol since 2001 and has held the post of Senior Lecturer since 2007. He obtained his B.Eng. degree from the University of Bath in 1996 and his Ph.D. from the University of Bristol in 2001. He has lead collaborative projects with a number of industrial partners, including Toshiba and Kyocera and now leads Bristol's involvement in the MVCE's project on Green Radio. His research interests cover a variety of wireless communications techniques. Having originally specialised in physical layer work and OFDM in particular, he has in recent years expanded his interest to cover more MAC and RRM aspects of wireless and has embraced a cross layer approach to wireless system design. This has been applied in recent years to specific standards such as 802.11, 802.16, and LTE as well as to core theoretical work. This work has resulted in approximately 100 papers published in international journals and conferences and 11 patents. The majority of the latter are now owned by industry.



Angela Doufexi is currently Senior Lecturer in Wireless Networks at the University of Bristol. She graduated from the University of Athens with a B.Sc. in Physics in 1996. She received her M.Sc. in Electronic Engineering from Cardiff University in 1998. She then joined the Centre for Communications Research at the University of Bristol, where she received her Ph.D. in 2002. She has worked in a number of projects including the European IST projects SATURN, ROMANTIK, WCAM and ASTRALS. Her research interests include OFDM and OFDMA systems, multiuser diversity and resource allocation, wireless LANs and WiMax (PHY and MAC), space time coding and MIMO, LTE and 4th generation communications systems, cognitive radio, and multimedia transmission. She has published over 90 journal and conference papers in these areas.