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An Investigation of Dynamic Sub-carrier Allocation in OFDMA Systems

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Abstract—**Orthogonal Frequency Division Multiple Access (OFDMA) systems commonly operate with a pseudo-random allocation of active sub-carriers to users. However, dynamic (multi-user) sub-carrier allocation (DSA) in an OFDMA system with a SISO channel has been investigated previously in [1,2]. In this paper, an alternative algorithm is proposed and evaluated. Simulation results identify gains of up to 10dB and show that near identical gain is achieved for all users.**

Keywords- MIMO, OFDMA, Adaptive modulation.

I. INTRODUCTION

OFDMA has recently been chosen for the IEEE 802.16a and DVB-RCT standards [3,4]. It makes use of OFDM modulation whilst allowing multiple access by separating data symbols from different users in the frequency domain with fine granularity by the allocation of different (orthogonal and overlapping) sub-carriers. Hence, in a given time slot, all or some of the active sub-carriers can be used by a given terminal. OFDMA therefore concentrates uplink transmit power into a 'sub-channel' (an aggregation of sub-carriers) which consists of 1-Nth of the whole bandwidth (where N is typically the number of user terminals), resulting in a $10\log_{10}N$ dB gain.

Further to this uplink processing gain, multi-user diversity may be exploited to maximize utilization of the channels. In a frequency selective channel, sub-carriers will perceive a large variation in channel gain and the perceived channel will be different for each user. If an intelligent and deterministic rather than random allocation of sub-carriers is employed, this diversity can be exploited to ensure that the majority of sub-carriers allocated to each user perceive gain (relative to the mean) rather than attenuation. Algorithms to achieve a desirable allocation of sub-carriers to users have been proposed previously, including [1,2]. An alternative, adaptive multi-user Dynamic Sub-carrier Allocation (DSA) algorithm is proposed here in which the channel gain of each user is used as the metric to allocate the sub-carriers. As well as achieving significant diversity gains in addition to the OFDMA processing gain (as will be seen below), this algorithm has merits in comparison to others including a fair allocation of resources to users.

This paper investigates the performance of this algorithm. An OFDMA system model is presented in section II. The DSA algorithm is defined in section III. Simulation parameters are presented in section IV. Section V presents results leading to conclusions in section VI.

II. SYSTEM MODEL

The OFDMA system considered here includes one Base Station (BS) and multiple Mobile Stations (MSs). In this paper, the downlink is considered for the sake of simplicity. However, the DSA algorithm and the diversity gains which it achieves are equally applicable to the uplink (which will enjoy the further benefits of OFDMA processing gain). The BS is considered to communicate simultaneously with multiple MSs, each of which is allocated a single sub-channel consisting of a given number of OFDMA sub-carriers (equal numbers of sub-carriers per sub-channel and a single sub-channel per MS is assumed for simplicity in this paper but this is not essential to the functionality of the DSA algorithm).

The system considered is presented in the form of a block diagram in Figure 1. The downlink process is shown for the case of a single user for simplicity. The BS takes the downlink data for all MSs and applies independent bit level error control coding, symbol mapping and serial to parallel conversion. A DSA mapping process allocates the parallel data symbols to appropriate sub-carriers as indicated by the DSA algorithm. OFDM modulation via Inverse Fast Fourier Transform with subsequent Guard Interval (GI) insertion and parallel to serial conversion is implemented.

The signal received by the MSs takes the form of the BS signal, convolved with the channel transfer function matrix and additionally subject to AWGN. Symbols sent by the BS to other MSs (users) may be discarded after the FFT in the MS receiver.

Each MS receiver extracts the GI, applies a serial to parallel conversion and a Fast Fourier Transform. Based on the allocation of sub-carriers determined by the DSA algorithm, those sub-carriers assigned to a given MSs sub-channel are extracted. Channel estimation, Equalisation and soft de-mapping yield bit level information which is then subject to error control. In this paper, convolutional encoding, CSI-enhanced soft Viterbi decoding and block interleaving are assumed but the DSA algorithm is again independent of such issues.
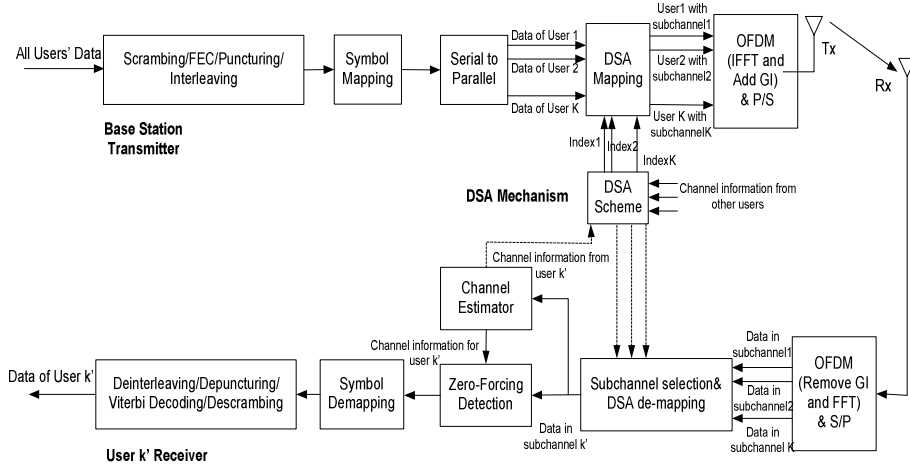
Figure 1.   System Model: OFDMA with DSA (1 MS)

III.   THE DSA ALGORITHM

In this section, an algorithmic definition of the proposed DSA scheme is provided. In the following, P_k represents the average received power for user k, K is the total number of users, N is a vector containing the indeces of the useable sub-carriers (i.e. $N = \{1,2,3...N_{Sub}\}$, where N_{Sub} is the total number of useable sub-carriers). $h_{k,n}$ is the channel gain (relative to the mean) for user k and sub-carrier n. $C_{k,s}$ is a matrix to record the location of allocated sub-carriers for user k and sub-carrier (within the sub-channel) s. $0_{N_{Sub}}$ is a vector of zeros of length N_{Sub}.

I. Initialization

Set $P_k = 0$ for all users $k = 1...K$

Set $C_{k,s} = 0$ for all users $k = 1...K$

Set $s = 1$

II. Main process
While $N \neq 0_{N_{Sub}}$

{(a) Make a short list according to the users that have less power[1]. Find user k satisfying

$P_k \leq P_i$ for all i, $1 \leq i \leq k$

(b) For the user k chosen in (a), Find sub-carrier n satisfying

$$\left| h_{k,n} \right| \geq \left| h_{k,j} \right| \qquad \text{for all } j \in N$$

(c) Update P_k, N and $C_{k,s}$ with the n from (b) according to:

$$P_k = P_k + \left| h_{k,n} \right|^2$$

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[1] For the first iteration (when no sub-carriers have been allocated and hence all users have equal power) the list may be entirely arbitrary.

$$N_n = N_n - n$$

$$C_{k,s} = n$$
$$s = s + 1$$

(d) go to the next user in the short list determined in (a) until all users are allocated another sub-carrier.

Thus, the algorithm operates by ranking users in order of current allocated (mean) channel gain from lowest to highest. Subsequently, additional sub-carriers are allocated to users in rank order allowing those with the lowest allocated gain to have the next 'choice' of sub-carrier. The operations in the algorithm thus largely consist of sorting, comparing and simple arithmetic.

IV.   SIMULATION ENVIRONMENT AND PARAMETERS

The Performance of the DSA algorithm is evaluated by simulation. The simulation considers COFDM (constraint length 7 convolutional code with CSI-enhanced soft Viterbi decoding) operating with a bandwidth of 100MHz as a candidate mobile broadband WWAN '4G' physical layer. Two data rate examples are considered (one derived from QPSK modulated symbols with rate-1/2 coding the other derived from 64-QAM modulated symbols with rate-3/4 coding).

To be representative of a mobile WWAN scenario, NLOS, wideband Rayleigh fading channels are modeled as tapped delay lines with either 250ns or 370ns RMS delay spread (normalized RMS delay spreads of 25 and 37 respectively). Thus, the system perceives a channel which is very much wideband; each sub-carrier is much narrower than the coherence bandwidth of the channel, facilitating the flexibility and fine granularity that the DSA algorithm exploits to achieve multi-user diversity.

2000 independent identically distributed (iid) quasi-static random channels samples per user are used in each simulation and the sub-carrier allocation is updated via the

DSA algorithm for each such sample. Results are presented in the form of BER as a function of received SNR.

It is assumed here that the DSA algorithm is implemented by the BS and that the BS has perfect knowledge of the channel gain matrix and uses this to determine sub-carrier allocation. Furthermore, it is assumed that the MSs have perfect knowledge of the channel transfer function for those sub-carriers allocated to them and that this is used for equalisation and decoding purposes.

For OFDMA and DSA algorithms, 16 users are considered and there are 768 usable sub-carriers in all. Therefore 48 sub-carriers are allocated to each sub-channel with one sub-channel per user. Simulation parameters are summarized in Tables I and II.

TABLE I. MODULATION PARAMETERS

Modulation	QPSK	64-QAM
Coding Rate	1/2	3/4
Data bits per sub-channel (48 sub-carriers)	48	216
Data bits per OFDM symbol (all 16-channels)	768	3,456
Total Bit Rate [Mbit/s]	64	288
Coded bits per sub-channel (48 sub-carriers)	96	288

TABLE II. CHANNEL MODELS

Name	'E'	'V'
RMS delay spread (ns)	250	370
Excess delay (ns)	1760	2690

V. PERFORMANCE COMPARISON

Simulation results for the BER performance of the OFDMA system considered both with and without the DSA algorithm are presented in Figures 3-6.

Figure 2 shows an example instantaneous wideband channel response in the frequency domain for a single user and the corresponding sub-carrier allocation. This serves to illustrate the multi-user diversity benefit which the DSA algorithm is able to achieve. It can be seen that the sub-carriers allocated in this instance have consistently high gain (all are higher than the mean for the channel over all sub-carriers) and a much flatter response than the actual channel. These factors lead to the substantial performance gains discussed below. It can also be intuitively seen how an alternative user perceiving an uncorrelated channel response could derive similar benefit from a different set of sub-carriers. It can also be seen that a clustered sub-carrier allocation would be unable to achieve this consistently high gain allocation.

Figure 3 compares the mean performance of all 16 users in channel 'E' when operating at 64Mbit/s (1/2-rate QPSK) both with and without DSA. It can be seen that very substantial gains (~11dB at 10^{-4} BER) can be achieved by DSA. Whilst this may seem surprisingly high, it must be considered in the context of the large amount of multi-user diversity gain evident in Figure 2.
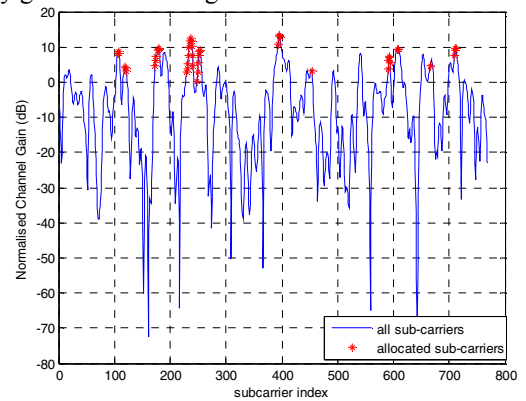

Figure 2. Example Channel Response and Sub-carrier Allocation
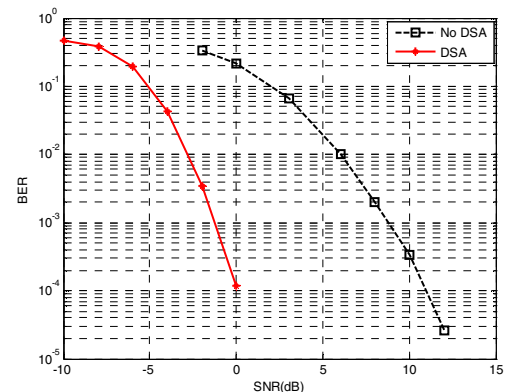

Figure 3. Average performance of all users in channel 'E' (64Mbit/s).

Figure 4 compares the performance of a sample of different users in the system employing DSA again for channel 'E' and the 64Mbits/s data rate (the average performance without DSA is shown again for reference). It can be seen that the performance of the users is extremely consistent, there is minimal variation in performance (as a function of received SNR) between users. Only a sample of the 16 users are shown for clarity, the sample shown are however a fair representation of the full set of users – performance gains *are* consistent across all users.
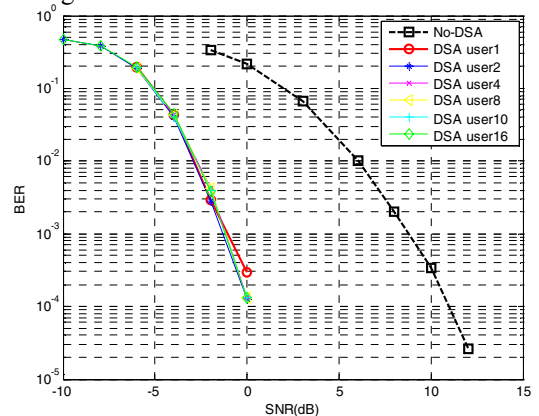

Figure 4. Performance of a sample of different users in channel 'E' (64Mbits/s).

It should be noted that user performance is 'equal' on the basis of a comparison of BER against received SNR. Thus, the gain provided to each user by DSA is equal. This does not imply however that the performance of all users is truly equal (this is not likely in a real world environment where fast fading, shadowing and free space attenuation will result in spatially diverse users seeing substantially different radio propagation conditions) nor that the DSA algorithm acts to compensate disadvantaged users.

Figure 5 shows the performance gain achieved by DSA in channel 'V' again for the 64Mbit/s data rate. Again, substantial benefits are evident (~7dB at 10^{-4} BER).
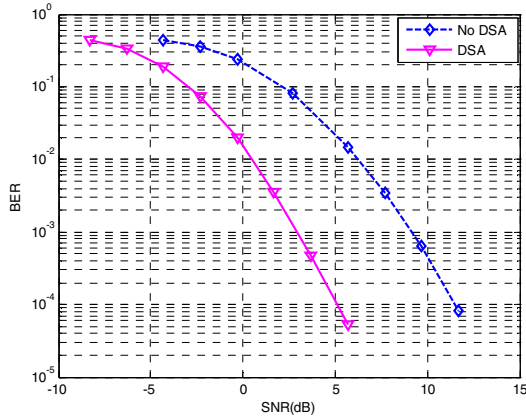

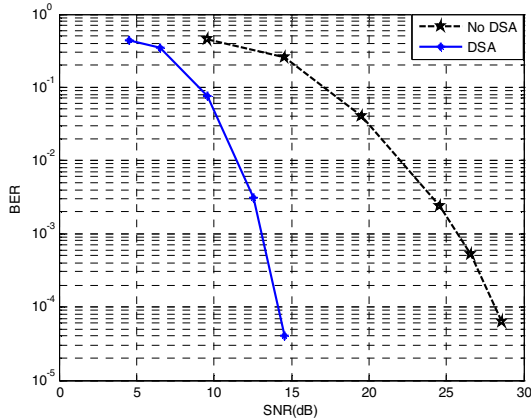Figure 5.   Average performance of all users in channel 'V' (64Mbit/s).

Figure 6.   Average performance of all users in channel 'E' (288Mbit/s).

Figure 6 shows the performance gain achieved by DSA in channel 'E' for the case of the 288 Mbit/s data rate. Whilst the higher modulation order and coding rate naturally results in increased SNR requirements, the gains achieved by the DSA algorithm are actually higher (~14dB and 10^{-4} BER). This can be attributed to the fact that the heavily punctured 3/4-rate code is less able to average errors in the highly

frequency selective channel perceived by the receiver in the case where DSA is not employed. When DSA is employed, as described above, it has the effect of reducing the variation of the perceived channel in the frequency domain, thereby reducing the requirement for the code to average out fading effects. This implies that DSA has the benefit of facilitating the use of higher rate error correcting codes.

VI.   CONCLUSIONS

In this paper, an algorithm for Dynamic Sub-Carrier Allocation has been proposed and evaluated in terms of performance in a '4G' mobile broadband WWAN context. Results show that the DSA algorithm is capable of exploiting the flexibility of fine granularity frequency allocation facilitated by OFDMA to derive substantial performance gains from multi-user diversity. Different modulation and coding schemes for different data rates and different channel scenarios have been considered. Results show that gains vary between 7 and 14dB depending upon the channels and modulation and coding schemes considered and that the gains are consistent across users implying that the algorithm has the additional benefit of achieving a very fair distribution of multi-user diversity benefits between users. The results for higher data rates also imply that DSA facilitates the use of higher rate FEC codes.

Analysis presented here is based on the assumption that ideal channel estimates are available to support both equalization and decoding in the MS receiver and DSA in the BS. MSs are also assumed to always know which sub-carriers are allocated to them. Mechanisms to support the necessary exchange of control information and the effects of non-ideal channel estimates are obvious topics for further research.

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