Cross-layer adaptive techniques for throughput enhancement in wireless OFDM-based networks *

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Abstract

The employment of sophisticated adaptation techniques across all layers is indispensable in order to ensure quality of service to users and enhance wireless system performance. Independent consideration of layers simplifies system design but is often inadequate due to co-channel interference among users that reuse spectrum and the impact of local adaptation actions on overall system performance. In this work, we identify issues that arise from the synergy between the physical and the media access control (MAC) layers in the context of Orthogonal Frequency Division Multiple Access (OFDMA). We address the problem of channel allocation, modulation level and power control in a system with several access points (APs). In such a system, it is important to identify co-channel sets of users from different APs and assign transmission parameters to each AP-user link, so that the total achievable system rate is maximized. We study the impact of such adaptive techniques on co-channel interference and channel reuse, which essentially affect system rate. We present a class of centralized heuristic algorithms for constructing co-channel sets of users. The algorithms use greedy assignment criteria, such as induced and received interference to and from other co-channel users, contribution to rate increase and minimum signal-to-interference ratio (SIR) per subcarrier. Numerical results illustrate the performance benefits of this cross-layer approach and demonstrate the relative impact of different parameters on system performance.

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1 Introduction

Wireless broadband access is necessitated by a clear need for ubiquitous coverage and connectivity in personal, local or wide area networks and an increasing demand for rate-demanding services as well as for mobility, flexibility and easiness of system deployment. Third generation (3G) cellular systems such as UMTS and cdma2000 provide high and diverse data rates up to 2 Mbps in a wide area environment. Other technologies evolve as a complement to 3G systems and aim at providing service in different environments. In fixed broadband wireless access (FBWA), buildings are connected to base stations (BSs) that are wired to the backbone network. FBWA is specified by IEEE standard 802.16. Wireless local area networks (WLANs) operate in a local environment, either in a distributed coordination function (DCF) mode, where users are connected to each other in multiple hops, or in a point coordination function (PCF) mode with single-hop user connection to a central access point (AP). WLAN standards IEEE 802.11a and 802.11b achieve 54 and 11 Mbps respectively. Finally, wireless Personal Area Network (WPAN) technologies such as Bluetooth and HomeRF focus on short-range interconnection among different equipment (printers, PDAs, home appliances) and are specified by IEEE standard 802.15.

Orthogonal frequency division multiple access (OFDMA) is a proposed signaling and access techniques for wireless broadband networks [1]. OFDMA is included in IEEE 802.11a [2] and ETSI HIPERLAN/2 WLAN standards and is also proposed by IEEE 802.15 and 802.16 working groups. In OFDMA, the wide-band spectrum is divided into orthogonal narrow-band subcarriers as in frequency division multiplexing and the bit stream is splitted into subsets, the subsymbols. Each subsymbol modulates a subcarrier and subsymbols of a user are transmitted in parallel over subcarriers. Subsymbol orthogonality is preserved by appropriate subcarrier spacing. This leads to much higher spectral efficiency than in simple frequency division multiplex and high achievable data rates. OFDM transmission reduces the effective symbol transmission rate and provides high immunity to inter-symbol interference (ISI). It also provides additional flexibility by allowing adaptation for each subcarrier [3].

The primary goal in a wireless system is to fulfil quality of service (QoS) requirements of users. At the physical layer, QoS is synonymous to an acceptable signal-to-interference-and-noise ratio (SINR) level or bit error rate (BER) at the receiver, while at the MAC or higher layers, QoS is expressed in terms of minimum achievable rate or maximum tolerable delay guarantees. QoS provisioning and enhancement of system throughput depend on mechanisms that span several layers. At the MAC layer, QoS guarantees are provided by scheduling and channel allocation methods. At the physical layer, adaptation of modulation level and symbol rate controls sustainable interference and delay spread for a maximum acceptable BER respectively [4], while transmission power control adjusts interference at receivers so as to provide acceptable connections to users.

The main goal of power control is to balance receiver signal-to-interference ratios (SIRs) of co-channel links. In the initial centralized approach [5], the maxmin achievable common link SIR was $\gamma^* = 1/(\lambda^* - 1)$, where λ^* is the maximum positive real eigenvalue of a matrix with scaled transmitter-receiver link gains. Distributed iterative algorithms that achieve the same goal with local SIR measurements have also been proposed [6], [7]. Qiu *et.al.* [8] study joint modulation and power control for rate maximization for a set of co-channel BS-user pairs. Assuming continuous rates, their algorithm maximizes the product of SINRs but can be suboptimal in maximizing total rate. Fong *et.al.* [9] consider a multi-cell system with one carrier frequency and apply scheduling of concurrent BS transmissions and slot allocation so as to maximize system capacity. The proposed Staggered Resource Allocation (SRA) attempts to minimize inter-cell interference in each cell. In [10], an iterative algorithm for joint power control and BS assignment for the up-link is proposed. The algorithm converges to a feasible solution, if there exists one, and this minimizes total transmitted power. In [11], a heuristic algorithm for BS, power and channel allocation is presented, that attempts to provide acceptable link quality by using a reduced number of channels.

The power allocation across parallel orthogonal channels that maximizes information-theoretic rate for one user with additive white Gaussian noise and a total power constraint is found by water-filling. The bit allocation for each channel (OFDM subcarrier) is specified by the power allocation. In single-cell multi-user systems with given subcarrier allocation to users and a total power constraint for each user, water-filling allocates power across subcarriers of each user. The problem with unknown subcarrier assignment is difficult due to the discrete nature of subcarrier allocation. Given the different quality of each subcarrier for different users, finding the optimal subcarrier allocation to users and bit and power allocations that maximize total rate is a hard problem. In [12], the discrete problem is relaxed into a continuous optimization one that can be solved with numerical methods. Rounding of the continuous solution does not incur significant rate losses. In [13], the dual of this problem is studied, namely subcarrier, bit and power allocation for total power minimization and satisfaction of minimum rate constraints of users. The continuous relaxation of the integer programming problem leads to an iterative algorithm with a suboptimal solution.

In a multi-cell system, the problem becomes more difficult even for given subcarrier assignment, due to co-channel interference among users that reuse subcarriers in different cells. If the number of co-channel users is relatively large, the interference perceived by a user in a subcarrier is approximately Gaussian based on central limit theorem and water-filling can be applied. If this approximation is not valid, finding the power allocation that maximizes total rate is a non-trivial problem even for one subcarrier, since the power allocated to a user becomes interference to co-channel users. If subcarrier allocation is not given, all possible user combinations need to be checked so as to identify the appropriate co-channel set for each subcarrier. In [14], a heuristic distributed algorithm is presented, that is executed independently by each BS and is based on iterative water-filling on a set of subcarriers and removal of subcarriers where SINRs are violated. In the preliminary work of [15], we presented a greedy heuristic for joint channel allocation, modulation level and power control in a multi-cell system with a generic access scheme with orthogonal channels. In multi-channel systems, the AP assigns each channel to the user with the least measured interference and adjusts transmission parameters separately for each user. Thus, it selects the highest modulation level for which there exists a power level within power range that ensures acceptable SINR. APs take turns in the allocation based on a staggered protocol [16]. Channel reassignment is performed if the highest power level and lowest modulation level do not provide acceptable SINR in the current channel. Therefore, each AP does not consider the impact of adaptation and allocation actions on users in other cells. This clearly separates physical layer adaptation from MAC layer channel allocation and leads to suboptimal performance.

However, co-channel interference among users that reuse the limited spectrum and the impact of local adaptation actions on system performance impose layer interactions. Physical layer parameters affect multiple access, since they control interference and user tolerance to it. Adaptation of these parameters affects QoS at the physical (e.g., BER, SINR) and higher layers (e.g., transmission rate). MAC layer channel allocation in a cell affects interference of users in other cells and triggers physical-layer adaptation actions. If coordination among APs is allowed through high-speed wireline or wireless links, channel allocation and transmission adaptation can be studied jointly. This cross-layer approach would improve QoS across all layers. Furthermore, since each subcarrier in OFDMA has different quality per user, it is important to identify appropriate co-channel user sets for each subcarrier. Co-channel interference and user susceptibility to it can be controlled by selective insertion of users in subcarriers and transmission control. Then, users can have acceptable SINRs and be maximally "packed" in each subcarrier, so that system rate is increased.

We address the joint problem of channel allocation, modulation level and power control in a network with several APs and fixed AP assignment. Our objective is to study the impact of these parameters on co-channel interference and channel reuse, which characterize system rate. Using the essential feature of channel orthogonality as a baseline, our approach places emphasis on OFDM, which presents some novel challenges in resource allocation and provides additional flexibility in adapting transmission to varying channel conditions. We present a class of centralized greedy heuristic algorithms for constructing co-channel sets. We attempt to capture interdependencies between MAC and physical layer and to identify the arising issues and performance benefits of this unified approach. The rest of the paper is organized as follows. In section 2, we present the adopted model and assumptions. In section 3, we state the problem and characterize its complexity. The proposed algorithms are described in section 4. Optimal solutions for some special cases are derived in section 5 and numerical results are illustrated in section 6. Finally section 7 concludes the paper.

2 System model

A schematic diagram of a single-user OFDM transmitter and receiver with N subcarriers is depicted in figure 1. Packetized data from higher layers are decomposed into bits before transmission. The bit stream is divided into bit groups and each group defines one OFDM symbol. Assuming non-overlapping symbols, we focus on one OFDM symbol, the bits of which can be further divided into N bit subgroups. The bits of the nth subgroup are fed into the nth modulator and modulate the nth subcarrier, $n = 0, \ldots, N-1$. The complex subsymbol d_n at the output of the nth modulator is selected from a QAM or QPSK constellation. The modulation level of d_n depends on the number of allocated bits at subcarrier n, which in turn depends on subcarrier quality. All subsymbols are then fed into an inverse discrete Fourier transform (IDFT) module and are transformed into a sequence of time samples $\{x_i\}_{i=0}^{N-1}$ with $x_i = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} d_n e^{j2\pi in/N}$, where $1/\sqrt{N}$ is a scale factor and $j = \sqrt{-1}$. A cyclic prefix of ν samples with duration larger than the maximum delay spread is appended

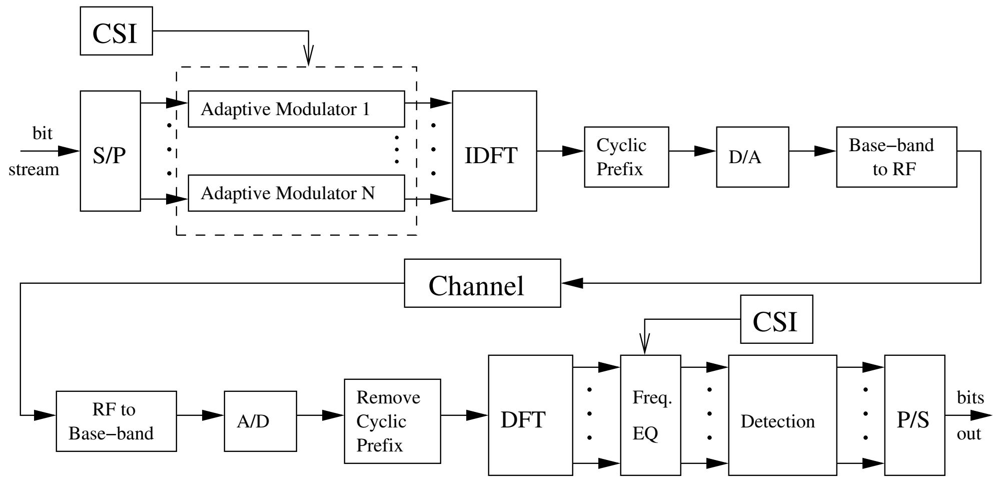

Figure 1: Single-user OFDM transmitter and receiver.

to the N time samples, as a means of eliminating ISI. The sequence $\{x_i\}_{i=0}^{N-1}$ is then passed to a D/A converter, whose output is the continuous signal

$$x(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} d_n e^{j2\pi nt/T}, \; 0 \leq t \leq T, \tag{1}$$

where the pulse-shaping filter $g(t)$ is normalized to 1 and T is the symbol duration. Since the time-domain signal is a superposition of N symbol pulses, the frequency-domain signal consists of N $sinc(\pi fT)$ functions, with the nth pulse shifted in frequency by n/T, $n = 0, 1, \ldots, N-1$. Since the $sinc(\pi fT)$ function is zero at integer multiples of $1/T$, subsymbols at different subcarriers can be distinguished at the receiver. The base-band signal $x(t)$ is up-converted and transmitted through the channel. The time-invariant channel impulse response for a symbol duration is $h(t) = \sum_{\ell=1}^{L} \beta_\ell \, \delta(t - \tau_\ell)$, where L is the number of paths in the multi-path and β_ℓ captures propagation effects such as path loss, shadow fading and link gain for the ℓth path. The received signal is the convolution of the transmitted signal and the impulse response. After its translation to base-band and removal of its cyclic prefix, it is given as $r(t) = \sum_{\ell=1}^{L} \beta_\ell e^{-j2\pi f_c \tau_\ell} x(t - \tau_\ell) + z(t)$, where f_c is the carrier frequency and $z(t)$ is the base-band noise process. Next, the signal is digitized by being sampled at time points kT/N, $k = 0, \ldots, N-1$. The kth sample of the received signal is

$$r_k = \frac{1}{\sqrt{N}} \sum_{\ell=1}^{L} \sum_{n=0}^{N-1} d_n \xi_\ell(n) e^{j2\pi nk/N} + z_k, \tag{2}$$

where parameter $\xi_\ell(n) = \beta_\ell e^{-j2\pi(f_c + n/T)\tau_\ell}$ captures the different impact of the ℓth path delay on different subcarriers n and z_k are noise samples. Samples $\{r_k\}_{k=0}^{N-1}$

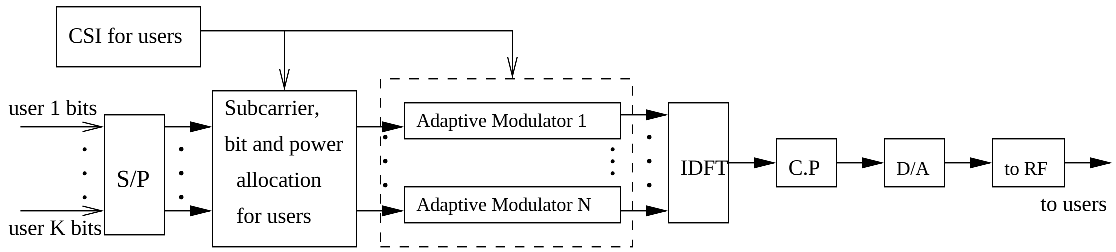

Figure 2: Multi-user OFDM transmitter diagram.

enter the DFT module and the received subsymbol at subcarrier n is given as $Y_n = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} r_k e^{-j2\pi nk/N}$. After some algebraic manipulation and due to subcarrier orthogonality, we have

$$Y_n = [\sum_{\ell=1}^{L} \xi_\ell(n)]d_n + z_n = g_n d_n + z_n,\ n = 0, \ldots, N-1. \tag{3}$$

where z_n is the noise at subcarrier n. Thus, received subsymbols are scaled versions of transmitted ones and complex parameter g_n captures the multi-path effects at n.

The receiver needs channel state information (CSI) in terms of frequency-domain channel transfer function at subcarriers so as to retrieve subsymbols. Channel estimation is performed with pilot symbols that are interspersed with data symbols. A pilot symbol e consists of known subsymbols $\{e_n\}_{n=0}^{N-1}$. The received pilot subsymbol at subcarrier n after DFT is $y_n = e_n g_n + z_n$. Then, the minimum-mean-squared-error (MMSE) estimate of g_n is $\tilde{g}_n = y_n/e_n = g_n + (z_n/e_n)$, for $n = 0, \ldots, N-1$. Estimates $\tilde{g}_n$ are used for frequency-domain equalization (FEQ), namely phase and amplitude compensation of received subsymbols before detection. In a slowly time-varying channel, the transmitter obtains reliable CSI and subcarrier modulation information via receiver feedback and the Maximum Likelihood (ML) detector decides about the transmitted subsymbol based on $Y_n/\tilde{g}_n$. If all transmitted subsymbols are normalized to unit power, the signal-to-noise ratio (SNR) at the nth subcarrier is $SNR^{(n)} = G^{(n)}/\sigma^2$, where σ^2 is the noise variance and $G^{(n)} = |g_n|^2$ is the link gain at subcarrier n. If transmission power $P^{(n)}$ is used in n, then $SNR^{(n)} = G^{(n)}P^{(n)}/\sigma^2$.

Consider now the down-link of a system with M APs and K users, with each user connected to the closest AP. A slotted TDMA frame is assumed. Within each slot of duration T_s, each AP sends data to its users with N subcarriers. Synchronization is assumed among corresponding slots of frames in different APs and among transmitted symbols within a slot. At each AP, packetized data arrive from higher layer queues and are decomposed into symbol streams before transmission. A multi-user OFDM transmission system for an AP is depicted in figure 2. User k has rate requirements of ρ_k bits/sec over interval $(0,t)$ of $\lfloor t/T_s \rfloor$ slots. This is the requested rate from the MAC layer. In order to achieve this rate, each user is assigned a symbol rate in symbols/sec. This equals $1/T$ for all users and slots, so that $S = T_s/T$ OFDM user symbols per slot are transmitted. Within a slot, user k is assigned a number of bits per OFDM symbol, $N_k = \sum_{n=1}^{N} b_{n,k}$, where $b_{n,k}$ is the number of bits of the nth subsymbol of k that modulates subcarrier n. OFDM symbols at subcarriers can consist of different number of bits depending on subcarrier quality. This number is selected from a L_0-element set $\mathcal{M}$ of available modulation levels with different number of bits per subsymbol, $\{b_i\}_{i=1}^{L_0}$. Subcarrier quality is fixed in a slot but it may vary between slots. For invariant channel in one slot, each one of the S OFDM symbols of a user in a slot is splitted into subsymbols over the same set of subcarriers. The rate of user k in a slot is N_k/T and the rate for the interval $(0,t)$ is $\sum_{s=1}^{\lfloor t/T_s \rfloor} N_k^{(s)}$, where $N_k^{(s)}$ is the number of bits per OFDM symbol of user k at slot s. We focus on subcarrier, bit and power allocation in a slot.

Clearly, users served by the same AP must be assigned different subcarriers, but users served by different APs may reuse the same subcarrier. The link between AP i and user j in subcarrier n is characterized by gain $G_{ij}^{(n)}$. A user j in subcarrier n receives useful signal from the serving AP and interference from other APs that transmit in n. Although useful and interfering signals are not synchronized in general, we consider symbol-synchronous reception. An assumption that the delay between reception of these signals does not exceed T would also suffice. Such assumptions are realistic for indoor environments with small distances among APs. At the receiver, the signal is sampled at the symbol rate. If user j is served by AP i_j, the average SINR at the matched filter receiver of j at subcarrier n is,

$$SINR_j^{(n)} = \frac{G_{i_j j}^{(n)} P_{i_j}^{(n)}}{\sum\limits_{i_k \in \mathcal{B}^{(n)}: k \neq j} G_{i_k j}^{(n)} P_{i_k}^{(n)} + \sigma^2}, \tag{4}$$

where $\mathcal{B}^{(n)}$ is the set of APs that use subcarrier n and $P_i^{(n)}$ is the transmission power of AP i in n. In our model, we assume that co-channel interference is the prevailing interference type and that noise is not known, so that the SINR is replaced by the signal-to-interference ratio (SIR). This approach also eliminates the need for total power constraints. If the noise is not included in (4), the SIR is insensitive to absolute power values $\{P_{i_k}^{(n)}\}$ and thus powers can always be adjusted in order to achieve a certain SIR. Furthermore, noise does not affect the feasibility of a power vector as far as satisfying a set of SIRs is concerned.

When a M-QAM modulation level is used in a subcarrier, where $M = 2^b$ for some $b \in \mathcal{M}$, BER is approximated as BER $\approx 0.2 \exp[-1.5(\mathrm{SIR})/M - 1]$ [17]. For a maximum acceptable BER of ϵ in a subcarrier, the SIR should satisfy

$$\mathrm{SIR} \geq \frac{-\ln(5\epsilon)}{1.5}(M-1)\,. \tag{5}$$

Thus, each modulation level b is mapped to a minimum required SIR $\gamma(b)$ (in dB), equal to the right-hand side of (5).

There exist two versions of the channel assignment problem. If user rate requirements are specified, the problem is to satisfy them with the minimum number of subcarriers. Otherwise, the objective is to maximize total achievable system rate. We refer to these problems as version I and II respectively. Version I aims indirectly at maximizing the number of accommodated users in the system, while version II aims directly at maximizing total rate.

3 Joint channel allocation, modulation/power control

A user receives useful signal from the serving AP in some subcarriers and interference from neighboring APs that use these subcarriers to transmit to other users. The AP can control modulation level and power in each subcarrier. Co-channel users in a subcarrier must belong to different APs. A co-channel user set is *feasible* if corresponding BERs at user receivers are acceptable. The feasibility of a co-channel user set depends on users and AP-user link gains. It also depends on user modulation levels, since these are associated with different SIR thresholds so as to maintain acceptable BER. A user modulation level vector that ensures a feasible co-channel user set is called feasible as well. When power is also controllable, the feasibility of a modulation level vector depends on power levels. Finally, co-channel set feasibility depends on the individual subcarrier, due to different gains of different subcarriers. Thus, feasible co-channel sets in a subcarrier may not be eligible in another subcarrier or subcarrier reuse may be feasible with lower modulation levels.

When a high modulation level is assigned to a user in a subcarrier, user rate is increased since more bits are transmitted. If high modulation levels are used, the user needs fewer subcarriers to satisfy rate requirements. Thus, more users are accommodated in the system and capacity is increased. However, high modulation levels do not facilitate subcarrier reuse, since they are vulnerable to interference. Hence, fewer users can coexist in the same subcarrier and from that point of view capacity is not increased. On the other hand, a low modulation level implies a small number of transmitted user bits. The user requires more subcarriers to satisfy rate requirements and thus fewer users are accommodated. However, low modulation levels favor subcarrier reuse since they sustain more interference and thus more users can be "packed" in the channel. Therefore, high modulation levels result in high rates for some users in a subcarrier but may lead to reduced *total* subcarrier rate due to smaller subcarrier reuse. Low modulation levels yield lower rates but may result in high subcarrier rate due to larger subcarrier reuse. When power control is incorporated, controlling transmission power of a user changes useful signal as well as interference for co-channel users. Power adaptation so as to achieve feasible modulation level vectors with high total rate for co-channel users is a challenging issue.

Clearly, there exists a tradeoff between achievable rate per subcarrier and subcarrier reuse. The question is whether there exists a way to jointly perform subcarrier allocation, modulation and power control, so as to maximize total rate for each subcarrier. This is equivalent to identifying co-channel user sets with maximum subcarrier rate. Ideally, we want to use high modulation levels and reuse the same subcarrier for as many users as possible. This is possible if users are close to serving APs, so that transmissions from other APs do not cause interference. However, when co-channel interference is an issue, subcarrier reuse may be feasible for some users with certain modulation levels.

3.1 Characterization of problem complexity

Consider the problem of identifying the feasible co-channel set with maximum subcarrier rate and fix attention to an instance with gains $G_{ij}^{(n)}$ between AP i and user j in subcarrier n. First, assume that power control is not used. Let $\mathcal{S}_i$ be the set of users served by AP i, $i = 1, \ldots, M$ and let b_j be the modulation level of user j. Fix attention to subcarrier n. An *assignment policy* is a rule that determines the set of co-channel users and corresponding modulation levels for n. The maximum cardinality of a co-channel set is M, since at most one user from each AP can use a subcarrier. An assignment policy consists of the following steps: (i) identification of an AP activation set, (ii) user selection (at most one user from each active AP) and (iii) modulation level (rate) assignment to users. First, some APs need to be activated for transmission. An AP activation set is represented by a $M \times 1$ binary activation vector $\mathbf{a}$, whose a_i entry is 1, if AP i belongs to the activation set, otherwise it is 0. Next, a user must be selected from each active AP. Given an activation vector $\mathbf{a}$, the interference experienced by a user is known and the selected user $u_i^*(\mathbf{a}, n)$ from AP i is the one with the highest modulation level among users in $\mathcal{S}_i$ and an acceptable BER. Thus,

$$u_i^*(\mathbf{a}, n) = \arg\max_{u \in \mathcal{S}_i} b_u = \arg\max_{u \in \mathcal{S}_i} \left\{ \max \left[b \in \mathcal{M} : \frac{G_{iu}^{(n)}}{\sum\limits_{j \neq i : a_j = 1} G_{ju}^{(n)}} \geq \gamma(b) \right] \right\} \ \forall i : a_i \neq 0 \tag{6}$$

where b_u is the modulation level of user u. Based on this user selection rule, activation vector $\mathbf{a}$ is associated with modulation vector $\mathbf{b}(\mathbf{a}, n) = (b_{u_1^*(\mathbf{a},n)}, b_{u_2^*(\mathbf{a},n)}, \ldots, b_{u_M^*(\mathbf{a},n)})$. If we repeat this procedure for the set $\mathcal{S}$ of all activation vectors, we find a set of modulation vectors $\{\mathbf{b}(\mathbf{a}, n) : \mathbf{a} \in \mathcal{S}\}$, which is called *set of achievable AP rate vectors for subcarrier n*. The assignment policy that maximizes total rate in n identifies the AP activation vector $\mathbf{a}^*(n)$ where the corresponding modulation vector has the maximum sum of entries over all vectors in $\mathcal{S}$, that is $\mathbf{a}^*(n) = \arg\max_{\mathbf{a} \in \mathcal{S}} \sum_{i=1}^{M} b_{u_i^*(\mathbf{a},n)}$. Such a vector is found for each subcarrier.

We now show that the problem above is NP-Complete. Consider a simple version of the problem with M APs, one user per AP and a modulation level b with SIR threshold $\gamma(b)$. The binary AP activation vector $\mathbf{a}^*$ that maximizes subcarrier rate corresponds to a feasible co-channel set and has the maximum number of active APs. If the gain between each AP and the served user is G and gains between an AP and users not served by this AP are 1, the objective is: maximize$_{\mathbf{a}} \sum_{i=1}^{M} a_i$, subject to the SIR constraint $G/(\sum_{i=1}^{M} a_i - G) \geq \gamma$ or $\sum_{i=1}^{M} a_i \leq G(1+\gamma)/\gamma$. This is identified as a $0-1$ Knapsack problem. Since this is an NP-Complete problem [18] and we converted it to an instance of our problem, our problem is also NP-Complete.

When power control comes into stage, the problem becomes more difficult. With no power control, we were able to select the appropriate user $u_i^*(\mathbf{a}, n)$ from each AP if the activation vector $\mathbf{a}(n)$ is given, since user SIR (and thus modulation level) is independent of modulation levels of co-channel users from other APs. This property does not hold when power control is present, since user SIR depends jointly on powers of all APs. Thus the selection of a user from each AP cannot be accomplished. In addition, even if the selected user from each AP is known, finding powers so as to maximize total subcarrier rate is not straightforward.

Consider $m \leq M$ selected co-channel users in a subcarrier. Let $\mathbf{G} = \{G_{ij}\}$ be the $m \times m$ matrix of link gains from AP i to user j, for $i, j \in \{1, 2, \ldots, m\}$. Let $\mathbf{b} = (b_1, b_2, \ldots, b_m)$ be the user modulation level vector and let $\boldsymbol{\gamma} = (\gamma_1, \gamma_2, \ldots, \gamma_m)$ be the corresponding SIR threshold vector. Define the AP transmission power vector $\mathbf{P} = (P_1, P_2, \ldots, P_m)$. The co-channel set is feasible if

$$SIR_j = \frac{G_{jj} P_j}{\sum_{i=1, i \neq j}^{m} G_{ij} P_i} \geq \gamma_j, \text{ for } j = 1, \ldots, m. \tag{7}$$

A modulation vector $\mathbf{b}$ is *achievable* for this co-channel set if there exists a power vector $\mathbf{P}$, so that SIR constraints corresponding to assigned modulation levels are satisfied for all m users. The co-channel user set is then *feasible with respect to* $\mathbf{b}$. Condition (7) is written $P_j \geq \sum_{i=1}^{m} (G_{ij}/G_{jj})(\gamma_j/(1+\gamma_j))P_i$, for $j = 1, \ldots, m$. Define a $m \times m$ matrix $\tilde{\mathbf{G}}$ with elements

$$\tilde{G}_{ij} = \frac{\gamma_j}{1+\gamma_j} \frac{G_{ij}}{G_{jj}}. \tag{8}$$

Then, condition (7) is written in matrix form as

$$\mathbf{P} \geq \mathbf{P}\tilde{\mathbf{G}}. \tag{9}$$

Matrix $\tilde{\mathbf{G}}$ is non-negative definite and irreducible. From Perron-Frobenius theorem, it has exactly one positive real eigenvalue $\lambda^{=} \max\{|\lambda_i|\}_{i=1}^{M}$, where $\{\lambda_i\}_{i=1}^{M}$ are the eigenvalues of $\tilde{\mathbf{G}}$. Eigenvalue λ^* has an associated eigenvector $\mathbf{P}^*$ with strictly positive entries. Furthermore, the minimum real λ such that inequality $\lambda \mathbf{P} \geq \tilde{\mathbf{G}}\mathbf{P}$ has solutions $\mathbf{P} > 0$ is $\lambda = \lambda^*$. We start by finding the maximum real positive eigenvalue λ^* of $\tilde{\mathbf{G}}$ to guarantee a power vector with positive entries. If $\lambda^* \leq 1$, then (9) holds and modulation vector $\mathbf{b}$ is achievable. The power vector that achieves $\mathbf{b}$ is the eigenvector that corresponds to λ^*.

Fix the activation vector $\mathbf{a}$ and define $\mathcal{F}$ as the set of all $\prod_{i=1}^{M}(|\mathcal{S}_i|+1)$ combinations of selected users from APs. Each pair $(\mathbf{a}, f)$, with $\mathbf{a} \in \mathcal{S}, f \in \mathcal{F}$ denotes a co-channel set $\mathbf{u}(\mathbf{a}, f, n) = \{u_i(\mathbf{a}, f, n) : i = 1, \ldots, m,\, u_i \in \mathcal{S}_i\}$. The assignment policy that maximizes total rate in n is given by $(\mathbf{a}^*, f^*) = \arg\max_{\mathbf{a} \in \mathcal{S}, f \in \mathcal{F}} \sum_{i=1}^{M} b_{u_i(\mathbf{a}, f, n)}$, provided that modulation vector $\mathbf{b} = (b_{u_i(\mathbf{a}, f, n)} : i = 1, \ldots, M)$ is achievable through a power vector. When the activation vector and the co-channel set are specified, the optimal achievable modulation vector is the one with the maximum sum of entries over all L_0^m possible vectors.

In the case of a slotted time schedule, different activation vectors for each subcarrier are used in different time slots so as to achieve given user rates or properties such as fairness. However, in this work we focus on assignment policies within a slot.

4 Proposed heuristic algorithms

Since enumeration of AP activation vectors and co-channel sets is of exponential complexity, it is desirable to design heuristic algorithms to construct co-channel sets with high subcarrier rate. The key idea is to ”pack” as many users as possible in each subcarrier and use high modulation levels. Each subcarrier is considered independently due to orthogonality. We present two greedy heuristic algorithms with different preference criteria for user allocation. In order to maintain reasonable complexity, the algorithms involve sequential user assignment in a subcarrier and no user reassignments. However, we allow modulation level reassignments for co-channel users. The order in which users are inserted in a subcarrier is crucial, since interference must be small so as to maintain acceptable SIRs for co-channel users. Power control is considered only when modulation adaptation alone cannot provide acceptable SIRs.

Algorithm A uses criteria such as induced interference to co-channel users, received interference from co-channel transmissions and amount of rate increase. At each step, an appropriate user is assigned to the subcarrier and modulation levels of other users are adjusted, so that acceptable SIRs are ensured. Fix attention to subcarrier n and let $\mathcal{U}^{(n)}$ be the set of users that are already assigned in n and $\mathcal{B}^{(n)}$ be the set of APs that transmit to users in $\mathcal{U}^{(n)}$. Let k be the user to be inserted next. User k should use n if gain $G_{i_k k}^{(n)}$ is high, so that high modulation level can be used. We also consider the interference that is caused by AP i_k serving user k to users in $\mathcal{U}^{(n)}$ and the interference caused to k from APs transmitting to other users in subcarrier n. We compute the maximum of these two interference values and define the *Signal-Interference Factor (SIF)* $F_{n,k}$ as

$$S_{n,k} = \frac{G_{i_k k}^{(n)}}{\max\left\{ \sum_{j\in\mathcal{U}^{(n)}} G_{i_k j}^{(n)}, \sum_{i_j\in\mathcal{B}^{(n)}} G_{i_j k}^{(n)} \right\}}. \tag{10}$$

Among candidate users, we select the one with the maximum SIF factor. By allowing the least interference increase in the system, future assignments are facilitated. If subcarrier n is empty, it is $S_{n,k} = G_{i_k k}^{(n)}$.

Consider now the effect of an inserted user on subcarrier rate. Let user k be tentatively inserted in n. Upon insertion, k receives interference from APs in $\mathcal{B}^{(n)}$. Furthermore, some users in $\mathcal{U}^{(n)}$ may not sustain the interference due to AP i_k, so that current SIR thresholds are violated. Modulation levels of these users must be reduced to ensure feasibility of the new co-channel set. The insertion of a user in a subcarrier is beneficial if subcarrier rate decrease due to users with violated SIRs is less than rate increase of new user, so that total subcarrier rate is increased. In fact, the most desirable user is the one for which rate increase is maximum. In order to formalize these rules, let $b^*_{n,k}$ be the maximum modulation level of k that leads to acceptable SIR upon its insertion in n. Let $\mathcal{V}_{n,k} \subseteq \mathcal{U}^{(n)}$ denote the set of users with violated SIR after insertion of k in n. For each user $m \in \mathcal{V}_{n,k}$, let b^-_m be the modulation level before insertion of user k and b^+_m be the maximum modulation level that ensures acceptable SIR after k is inserted. For subcarrier n and user k, define the *Incremental Rate Factor (IRF)* $T_{n,k}$ as

$$T_{n,k} = b^*_{n,k} + \sum_{m \in \mathcal{V}_{n,k}} (b^+_m - b^-_m). \tag{11}$$

If k is the first user to be inserted in n, then $T_{n,k} = b_{L_0}$. Users are assigned in a subcarrier in an efficient manner if they cause least interference to users in $\mathcal{U}^{(n)}$, receive least interference from APs in $\mathcal{B}^{(n)}$ and have large positive rate contribution. To capture these objectives, we define the *Assignment Preference Factor (APF)* $A_{n,k}$ for subcarrier n and user k as $A_{n,k} = S_{n,k}T_{n,k}$. Among users that cause or receive the same amount of interference, the more preferable is the one with the greatest rate benefit $T_{n,k}$. Among users with the same rate increase, the one with the smallest amount of received or induced interference is preferred. After user assignment, modulation levels are updated.

Since user assignment should not reduce the already achieved subcarrier rate, the sequential assignment of users terminates when $T_{n,k} < 0$ for all remaining users. Then, modulation control cannot further increase subcarrier rate. While modulation adaptation adjusts the level of sustainable interference for an acceptable BER, it does not actively change receiver SIRs. Transmission power control can be used with modulation adaptation so as to adjust useful signal and interference levels, improve subcarrier reuse and increase system rate. The goal is to identify an achievable modulation vector that leads to subcarrier rate increase. For the tentative assignment of user k, we start from the modulation vector whose entries equal b_{L_0} and use condition $\lambda^* \leq 1$ for the appropriate matrix to check if the modulation vector is achievable. If the vector is not achievable, we decrease the modulation level in one entry and check the vector again. This procedure is repeated until we find an achievable modulation vector with IRF $T_{n,k} > 0$. Then, we compute the SIF of k as

$$S_{n,k} = \frac{P_{i_k} G^{(n)}_{i_k k}}{\max\left\{P_{i_k} \sum_{j \in \mathcal{U}^{(n)}} G^{(n)}_{i_k j}, \sum_{i_j \in \mathcal{B}^{(n)}} P_{i_j} G^{(n)}_{i_j k}\right\}}, \tag{12}$$

where the powers are the entries of the eigenvector corresponding to the eigenvalue that is associated with the achievable modulation vector. If an achievable vector is not found, we set $T_{n,k} = -\infty$. The APF of user k is then computed as usual.

Algorithm B uses the IRF factor in (11), but it uses a different SIF factor: the assignment that maximizes the minimum user SIR in the subcarrier is selected over all possible assignments. Since users can have different modulation levels, SIRs are scaled by SIR thresholds. First, IRF factors $T_{n,k}$ for each user k are computed. If $T_{n,k} > 0$, the SIF factor is defined as $S_{n,k} = \min\left\{\frac{SIR_{n,k}}{\gamma_{n,k}}, \min_{j\in\mathcal{U}^{(n)}}\frac{SIR_{n,j}}{\gamma_{n,j}}\right\}$, where $\gamma_{n,k}$ and $\gamma_{n,j}$ are the SIR thresholds corresponding to modulation levels of users $k, j \in \mathcal{U}^{(n)}$. Algorithm B considers total induced interference, captures the impact of an assignment on co-channel users and attempts to balance scaled SIRs over all assignments. Thus, it attempts to increase the number of users with SIRs above thresholds. Finally, the APF factor is $A_{n,k} = S_{n,k}T_{n,k}$ and the user with the maximum APF is selected for assignment.

The main steps for both algorithms are summarized as follows.

- **STEP 0** : Activate only modulation control. Consider the first subcarrier n. Initialize list of candidate users, $\mathcal{L}$, to include all users. Compute APFs $A_{n,k}$ for users $k \in \mathcal{L}$.
- **STEP 1** : Select user $k^* \in \mathcal{L}$ with maximum APF and assign it to subcarrier n. Remove k^* and all users served by AP i_{k^*} from $\mathcal{L}$.
- **STEP 2** : If $\mathcal{L}$ is empty, go to Step 6. Otherwise compute APFs and IRFs of users in $\mathcal{L}$. If not all $k \in \mathcal{L}$ have $T_{n,k} < 0$, go to Step 1. If $T_{n,k} < 0 \, \forall \, k \in \mathcal{L}$ and power control is not active, activate power control. Go to Step 3.
- **STEP 3** : For each $k \in \mathcal{L}$, find an achievable modulation vector for users in $\mathcal{U}^{(n)}$ and user k, so that $T_{n,k} > 0$. (Start by all entries being b_{L_0} and reduce entries, until an achievable vector is found).
- **STEP 4** : If $T_{n,k} < 0, \forall \, k \in \mathcal{L}$, the assignment for subcarrier n is terminated. Go to step 5. Otherwise compute APFs and go to step 1.
- **STEP 5** : Proceed to subcarrier $n+1$ and repeat the procedure, until $n = N$.
- **STEP 6** : Replicate assignment for S slot symbols, wait for next measurement report and repeat procedure for all slots. If a user reaches rate requirements, do not consider it until all users reach their rate requirements.

The algorithms are centralized, since knowledge of gains of all AP-user links in all subcarriers is required. Known pilot symbols are splitted in subsymbols and are transmitted by APs in pre-determined mini-slots. By measuring useful signal and interference of pilot subsymbols in each subcarrier, a user estimates gains to all APs. It passes this information through the serving AP to a central controller, which is connected to all APs via high-speed links. After execution of A or B, the controller passes the outcome to APs to be transmitted to users.

Finally, a note about complexity. With modulation adaptation, the complexity of algorithms is $O(L_0 K M^2)$ per subcarrier. When power control is added, the computationally intensive part is the determination of an achievable modulation vector that involves eigenvalue computation. In the worst case of a $M \times M$ matrix, this has complexity $O(M^3)$ and may be required up to ML_0 times due to entry reduction of the modulation vector. Thus, power control results in $O(L_0 K M^5)$ complexity per subcarrier. Such complexities are not prohibitive for small or moderate-sized networks.

5 Optimal solution for special cases

We now provide optimal solutions for special cases of version I and version II of the problem.

For version I, consider $M = 2$ APs and let ρ_k be the rate requirements in bits/sec for user k. Let U_i be the set of users in AP i, $i = 1, 2$. Assume that a modulation level b with SIR threshold γ is used and first assume that power control is not used. The set of subcarriers to be allocated to users is assumed to form a sub-band, so that the gain of a AP-user link is fixed in all subcarriers. In order to minimize the number of subcarriers, we need to identify the maximum number of pairs of users from different APs, where each pair uses a subcarrier. The number of subcarriers needed for user k in a slot is $n_k = \lceil \rho_k T_s / Sb \rceil$.

Construct a bipartite graph $G = (U \cup V, E)$ as follows. Create one node for each required subcarrier of a user. Thus, $|U| = \sum_{k \in U_1} n_k$ and $|V| = \sum_{k \in U_2} n_k$. An edge (i, j) is added between nodes $i \in U$ and $j \in V$ (denoting subcarriers of users $\alpha \in U_1$ and $\beta \in U_2$ respectively) if $\min\{(G_{1\alpha}/G_{2\alpha}), (G_{2\beta}/G_{1\beta})\} \geq \gamma$ and these users can use the same subcarrier. A matching $\mathcal{M}$ in a graph G is a subset of edges of G, such that no two edges in $\mathcal{M}$ share the same node. An edge in $\mathcal{M}$ is called a matched edge. A maximum matching $\mathcal{M}^*$ is a matching of maximum cardinality. As an extension of a theorem stated in [19], we have:

Lemma 1 *For $M = 2$ APs, one modulation level and no power control, the minimum* *number of subcarriers to satisfy users equals the cardinality of a maximum matching in the bipartite graph plus the number of nodes that are not incident to a matched edge.*

The optimal assignment is as follows. Each edge in $\mathcal{M}^*$ denotes a pair of co-channel users. Assign each such pair to a different subcarrier. Then, assign to a separate subcarrier each user corresponding to a node that is not incident to a matched edge.

When transmission powers P_1 and P_2 are controllable, there exist powers P_1 and P_2 that lead to acceptable SIRs if and only if $\sqrt{G_{1\alpha}G_{2\beta}}/\sqrt{G_{1\beta}G_{2\alpha}} \geq \gamma$. Hence, an edge (i,j) is added to the bipartite graph between nodes $i \in U$ and $j \in V$ (denoting subcarriers of users $\alpha \in U_1$ and $\beta \in U_2$ respectively) if that condition is satisfied. The assignment of users to subcarriers is the same as in the previous case. The described approach does not hold for many modulation levels, since the number of required subcarriers is not known a priori.

For problem version II, consider one subcarrier and two AP-user links and consider continuous rates. The goal is to find transmission powers P_1, P_2 and rates b_1 and b_2 so as to maximize total rate. The maximum achievable rate with continuous rates represents an upper bound on the rate with discrete rates. The problem is formulated as follows:

$$\max_{(P_1,P_2,b_1,b_2)} (b_1+b_2) \text{ subject to: } \frac{G_{11}P_1}{G_{21}P_2} \geq c(2^{b_1}-1) \text{ and } \frac{G_{22}P_2}{G_{12}P_1} \geq c(2^{b_2}-1), \quad (13)$$

with $P_i, b_i \geq 0$, for $i = 1,2$ and $c = -\ln(5\epsilon)/1.5$ from (5). By using the standard method of Lagrange multipliers, we get the optimal solution,

$$b_1^* = b_2^* = (1/\ln 2)\ln\left(1 + (1/c)\sqrt{G_{11}G_{22}/G_{12}G_{21}}\right), \quad P_1/P_2 = \sqrt{G_{21}G_{22}/G_{11}G_{12}} \quad (14)$$

6 Performance results

We consider a 8km×8km area with 16 APs, with each AP located at the center of a square cell. Cells are arranged in 4 rows and 4 columns. Users are located in fixed random positions, uniformly distributed in the area. A user is served by the closest AP. APs and users have omni-directional antennas. Each AP-user link is characterized by path loss, shadow fading and multi-path. Path loss causes a decay of $1/d^4$ in received power at distance d from AP. Shadow fading is modelled by a log-normal random variable X with zero-mean and standard deviation $\sigma = 10$dB. Multi-path fading is modelled by a two-ray model. Each path has a complex Gaussian gain and

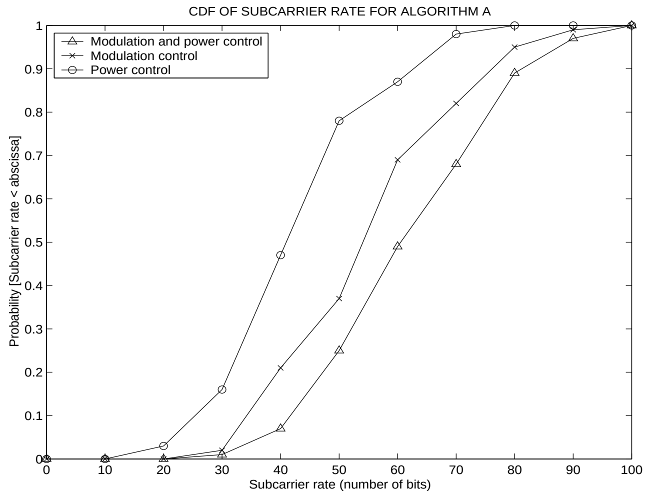

Figure 3: C.d.f. of total rate per subcarrier for algorithm A and different adaptation schemes.

delay that is uniformly distributed in $[0, T]$, where T is the symbol duration. The OFDM system has 20 subcarriers. Gain matrix $\mathbf{G}^{(n)}$ for $n = 1, \ldots 20$ is constructed with this model. A target BER of 10^{-3} is assumed and SIR thresholds are computed by (5). We compare the performance of different versions of algorithms A and B in terms of subcarrier rate, which is captured by total number of bits per subcarrier. For each experiment we generate random user locations. For each set of locations, we create a different instance of gain matrices per user per slot by changing shadow fading and multi-path and we find the average over $10,000$ such instances. Unless otherwise stated, each experiment is repeated for 100 random location sets. The outcome is the average of these experiments.

We want to compare the performance of algorithms A, B and assess the relative significance of modulation and power control. We consider the following schemes: (i) Modulation and power control. (ii) Modulation control only and (iii) Power control. In this case, only SIF factors are computed, since one modulation level is used. The algorithm checks the feasibility of a co-channel set for each candidate user with condition (9), which now becomes $((1+\gamma)/\gamma)\mathbf{P} \geq \mathbf{P}\hat{\mathbf{G}}$. Matrix $\hat{\mathbf{G}} = \{\hat{G}_{ij}\}$ has elements $\hat{G}_{ij} = G_{ij}/G_{ii}$. If the maximum eigenvalue λ^*, satisfies $\lambda^* \leq (1+\gamma)/\gamma$, then the co-channel set is feasible. SIF factors are computed with powers given by the eigenvector corresponding to λ^*.

Figure 3 depicts the cumulative distribution function (CDF) of subcarrier rate for algorithm A and the three methods above. When modulation control is controllable,

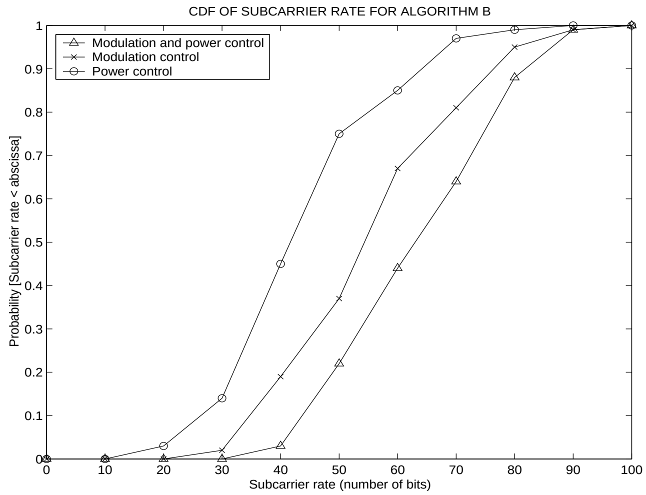

Figure 4: C.d.f of total rate per subcarrier for algorithm B and different adaptation schemes.

6 modulation levels were used, while in power control alone, the highest modulation level was used. For 16 APs, the maximum rate is 96 bits, since at most one user per AP uses a subcarrier. The achievable rate is limited by shadow fading and multipath. We observe that power control provides the lowest rate, while modulation control is better and joint modulation and power control yields the best performance. For example, with joint modulation and power control almost 50% of subcarriers achieve or exceed a rate of 60 bits, which implies that subcarriers are used efficiently. For power control, this percentage is only 15%. Joint modulation and power control achieves the best performance but it also increases complexity. When complexity is an issue, modulation control alone provides satisfactory performance. We note here the similarity of our results with those obtained in [8] for one channel. Similar trends are observed in figure 4 for algorithm B. Clearly, joint modulation and power control again achieves the best performance. However, algorithm B yields significant gains compared to A because of the different SIF factors. An improvement of $2-4\%$ is observed in percentages of subcarriers that achieve or exceed a certain rate. The improvement is more notable when modulation level is used, either alone or with power control.

Figure 5 shows the average subcarrier rate as a function of number of modulation levels. When k modulation levels are used, these are the ones with $b_1, \ldots, b_k$ bits/subsymbol. It is shown that addition of power control in an adaptive modulation scheme is beneficial up to a certain number of modulation levels. For example, for

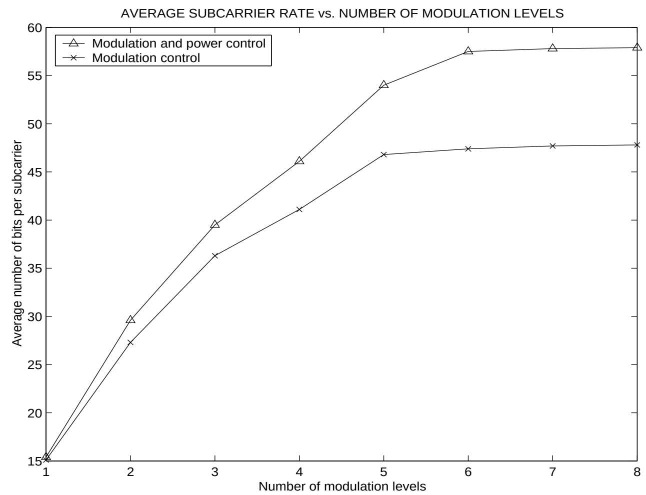

Figure 5: Average rate per subcarrier vs number of available modulation levels.

4 and 5 modulation levels that correspond to 16-QAM or 32-QAM, the performance gain of joint modulation and power control compared to that of modulation control, is doubled if we add a modulation level. This is because powers are controlled so that modulation vectors of higher rate are achievable. The use of additional modulation levels has marginal impact on performance.

In figure 6, the performance is depicted versus AP-user proximity. Sets of random locations were generated and for each set the average AP-user proximity was computed and mapped to path loss of the AP-user link. Assuming that APs transmit with fixed power, the initial SIR of user i is $SIR_i^0 = \left(\sum_{j=1,j\neq i}^{M} (d_{ii}/d_{ij})^4\right)^{-1}$, where d_{ij} is the distance between user i and AP j. Locations were generated until a sufficient number of scenarios with some average initial SIR was collected. A point of SIR xdB in the horizontal axis corresponds to user sets with initial SIRs in $[x, x+1]$dB. Low initial SIRs denote users that are located far from serving APs or close to interfering APs. Modulation control alleviates interference better than power control and achieves higher subcarrier rate. Power control does not provide good performance since the SIR balancing concept is not effective in high interference regimes. For milder interference conditions (higher SIR values), the difference in performance becomes less evident. Joint modulation and power control achieves the best performance.

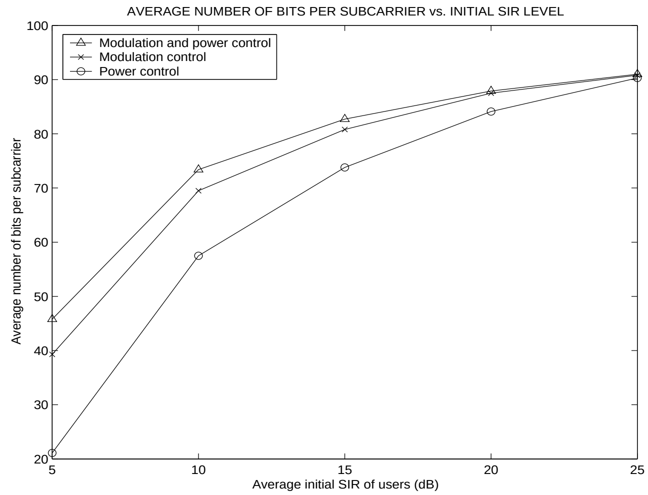

Figure 6: Average rate per subcarrier for different initial SIR values.

7 Discussion

We considered joint subcarrier allocation, modulation and power control in an OFDM system with several APs with the objective to maximize system rate. Using a cross-layer framework, we identified the impact of adaptation actions on channel reuse that affects achievable rate. We characterized problem complexity and presented centralized heuristic assignment algorithms. The scaled SIR balancing criterion achieves the best performance. In consistency with results for one channel, joint modulation and power control yields the best results.

There exist several directions for future study. Our approach can be extended to other multiple access schemes. In TDMA, different channel quality is triggered only by temporal channel variations. In CDMA with deterministic codes, channels are non-orthogonal codes with pairwise cross-correlation. A user that uses a code receives co-channel interference by other APs that use the same code, but it also receives cross-channel interference by correlated codes. The rate is controlled by spreading gain or modulation level adaptation. Similar tradeoffs arise here as well. Codes with low spreading gain achieve higher rates but have higher cross-correlation with other codes and are associated with lower SIRs.

In the presented snapshot model, we did not consider the impact of physical layer adaptation, arrival rates or channel variation on buffer dynamics since our study implied infinite-length buffers. It is meaningful to study subcarrier allocation and AP scheduling policies that maximize rate and maintain bounded buffer lengths. Further, our algorithms treat users with poor channel conditions unfairly, so that they may not satisfy rate requirements. It would be interesting to address the issue of fairness in rate allocation by specifying different fairness criteria. In OFDM, the problem is more challenging since rate allocation is performed in frequency domain with bit allocation to subcarriers and in time domain with scheduling. In a multi-cell system, additional degrees of freedom are AP activation set scheduling and user selection rules from APs. Based on the proposed centralized algorithms, another interesting topic would be to devise distributed algorithms that are executed independently by each AP and are easier to implement in real time. A user could then choose when to enter a channel, depending on incurred rate benefit.

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