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Channel State-Adaptive Techniques for Throughput Enhancement in Wireless Broadband Networks

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Channel state-Adaptive techniques for Throughput Enhancement in Wireless Broadband Networks

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Abstract— **Wireless broadband access is becoming increasingly popular in the telecommunications market due to the projected demand for flexible and easily deployable high-speed connections. In order to adhere to the volatility of the wireless medium, the adoption of sophisticated adaptation techniques is required. In this paper, we investigate the problem of enhancing channel throughput by performing resource assignment and reuse with adaptation of physical layer parameters. We propose an algorithm to allocate channels to users with different rate requirements, while appropriately adjusting the modulation level and transmission power, based on instantaneous channel quality. Our algorithm constructs the cochannel set of users in a sequential manner, by utilizing a criterion which is based on the induced and received amounts of interference for a user and the contribution in throughput increase. Although illustrated in the context of TDMA/TDD, the proposed technique can be applied in systems which support different multiple access and signaling schemes with orthogonal channels (e.g. OFDMA, CDMA). Our results indicate a considerable increase in throughput per utilized channel under such adaptive techniques.**

Keywords— **Wireless broadband networks, adaptive modulation, power control, resource assignment, multiple access.**

I. Introduction

The projected trend towards reliable high-speed communications has intensified the need for broadband access and services. Telecommuting, Internet access and enhanced multimedia services are typical instances where high data throughput is a prerequisite. While high speeds are readily achievable on the fiber internet backbone, the provisioning of "last mile" broadband access from the service provider to customers is cumbersome, since high data rates must be retained over existing wired infrastructures. Whereas a lot of attention has been concentrated on wireline broadband access techniques such as copper line, coaxial cable, xDSL [1] and cable modems [2], fixed wireless broadband access appears as an appealing solution, both for service providers and end-users, due to flexibility, easiness of system deployment and fast flow of revenues.

The ability to support high data rates in broadband wireless networks depends drastically on the availability and aggressive reuse of radio spectrum in all locations, as well as the use of efficient multiple access and signaling schemes. Intensive spectrum reuse guarantees achievability of high transmission rates, while appropriate multiple access techniques lead to efficient and flexible resource sharing and mitigate the impact of wireless channel impairments on system capacity. Currently envisioned wireless access schemes, such as Enhanced Data rates for GSM Evolution (EDGE) and Wideband Code Division Multiple Access (WCDMA), are expected to provide peak data rates of about 384 kbits/sec for macrocellular environments, based on single-carrier time and code division multiple access respectively [3],[4]. The principle of multi-carrier transmission, also known as Orthogonal Frequency Division Multiple Access (OFDMA), has been proposed as the wireless access and signaling scheme in several next generation wireless standards, as a means of achieving data rates of the order of 2-5 Mbits/sec in macrocells [5], [6]. In OFDMA, the available spectrum is divided into multiple orthogonal narrowband subchannels (subcarriers) and information symbols are transmitted in parallel over these low-rate subchannels. This method results in reduced intersymbol interference (ISI) and multipath delay spread, and thus improvement in capacity and attainable data rates.

Independently of the employed multiple access scheme, the foremost goal in a communications system is the fulfillment of Quality of Service (QoS) requirements for users, which is synonymous to achieving an acceptable data transmission rate, signal-to-interference-and-noise ratio (SINR) level or bit error rate (BER). However, wireless channel impairments and interference from neighboring locations and users impose certain constraints on achievability of data rates and SINR requirements. Identifying the performance limits of resource assignment and reuse with the objective to satisfy all users in the presence of cochannel interference and dynamicity of the wireless medium is therefore a challenging problem.

With respect to physical layer techniques, a first approach to satisfy the SINR requirements of users is the continuous adaptation of transmission power, based on channel quality. Although power control is beneficial for moderate resource reuse patterns, it leads to an increase of cochannel interference in intense channel reuse environments and may impose further constraints on capacity. The problem of achieving an acceptable SINR for all users through power control has been solved by Zander in [7]. Distributed versions of this algorithm have been proposed in [8], [9].

The employment of adaptive transmission techniques provides the potential to adjust parameters such as modulation level and symbol rate according to instantaneous quality of the channel, with the objective to maintain an acceptable BER without using more bandwidth. Although high modulation levels and symbol rates provide higher data throughput, they are more susceptible to interference and multipath delay spread respectively. In [10] and [11] the best combination of modulation level and symbol rate is derived based on feedback measurement information about interference and delay spread. Thus, higher modulation levels are assigned to users in good quality channels in order to exploit the existing SINR margin and increase throughput, whereas lower modulation levels are more robust to interference and are allocated to users in poor quality channels. Modulation adjustment can be coordinated by power control to further increase the Shannon capacity of the system, as demonstrated in [12].

Another approach towards resource provisioning is the utilization of Medium Access Control (MAC) layer techniques, namely sophisticated resource allocation algorithms. Given a set of users with certain requirements, an efficient algorithm should try to minimize the number of channels needed to accomodate users. By minimizing the number of channels at a given instant, the system can respond better to a potential sudden traffic increase or link deterioration. A plethora of algorithms for resource allocation has been studied in literature and a comprehensive survey on the topic is provided in [13]. In the context of packet-switched networks, resources are timeslots of a carrier frequency which is available in all cells. In the presence of intercell cochannel interference, the problem is to schedule concurrent transmissions of base stations and allocate timeslots to users, so as to maximize system capacity. Several algorithms with different degrees of base station coordination have been proposed. The main focus of [14] is on attempting to identify the main sources of interference for each cell and minimize their impact, by applying a special timeslot assignment and transmission scheduling for each sector of a cell, the so-called Staggered Resource Allocation algorithm (SRA). In [15], coordinated resource allocation and packet scheduling schemes, such as the Max-Min Scheduling Protocol (MMSP) are proposed, whereby transmission queue lengths and interference levels of users are considered. On the other hand, in Capture Division Packet Access (CDPA) scheme, transmissions from different base stations are uncoordinated. A base station transmits whenever it has a packet to transmit and transmission failures are amended with retransmissions [16].

The main shortcoming of such MAC layer-based schemes is that they do not consider transmission parameter control in conjunction with resource assignment. For instance, modulation level control and power adaptation are performed independently for each user, based on measurements obtained at each base station, without any consideration about the impact of a particular assignment on other users. As a result, resource utilization and reuse are inefficient and the aggregate system throughput is decreased. However, if some coordination among base stations is allowed, the formation of resource reuse patterns and the adaptation of transmission parameters can be studied jointly. The amount of introduced cochannel interference and the sensitivity of users to it can be controlled by selective insertion of users in the channel and adjustment of transmission parameters. Thus, users can meet their SINR requirements and be maximally "packed" in a channel, so that the total channel throughput is increased.

In this paper, we study cross-layer wireless access schemes. We investigate the performance of resource assignment and interference management, when combined with adaptive transmission techniques. Specifically, we focus on adaptive modulation, power control and resource allocation synergy to enhance network capacity and achieve high data throughput. We propose an algorithm to satisfy resource requirements for a set of users, while appropriately adjusting the modulation level and transmission power per utilized channel to achieve increased channel throughput. The main goals of our study are to identify the issues and benefits of this integrated approach, as well as to motivate further research on distributed versions of such algorithms, which would be easier to implement. Although illustrated in the context of a TDMA/TDD system, the proposed technique can be applied with some modifications in systems that support different multiple access and signaling schemes with orthogonal user channels, such as OFDMA and CDMA.

The paper is organized as follows. In section II we provide the model and the main assumptions used in our approach. In Section III, we describe the proposed algorithm of resource assignment with adaptive modulation and in section IV we enhance the algorithm by incorporating power control. In section V, the assignments for some special cases are derived and in section VI numerical results are illustrated. Finally section VII concludes our study.

II. System Model

A. System setup

Consider a wireless cellular network, consisting of M base stations and N users, with fixed and arbitrary locations with respect to bases. Each base provides coverage to a specific area, its cell and each user establishes connection with the nearest base. Resources consist of a single carrier frequency with a carrier frame of duration T_f, which is divided in timeslots, according to a TDMA scheme. The carrier frequency is utilized in every cell. Each slot constitutes a channel and adjacent channels of the same base station are perfectly orthogonal to each other. Users of the same base station must be assigned distinct channels. Perfect synchronization is assumed among carrier frames of different bases. The downlink and uplink connections between users and bases are implemented by time-division duplexing (TDD), namely by using two different time portions of the same carrier. In this work, we focus on the downlink portion and perform the resource assignment only for the downstream traffic.

Let $\mathcal{B}$ denote the set of base stations and suppose that user j is connected to base i_j. The path loss coefficients G_{ij} between each base i and user j are provided. They characterize completely the instantaneous propagation environment between them, in the sense that when base i transmits power P_i, user j receives power $G_{ij}P_i$. Each user j receives interference I_j from neighboring bases which transmit in the same downstream channel. For a given $M \times N$ path gain matrix $\mathbf{G} = \{G_{ij}\}$ and base transmission power vector $\mathbf{P}$, the SINR for user j in a channel is

$$W_j = \frac{G_{i_j j} P_{i_j}}{I_j} = \frac{G_{i_j j} P_{i_j}}{\sum_{k \in \mathcal{B}: k \neq j} G_{i_k j} P_{i_k}} \ . \qquad (1)$$

When power control is not considered and $P_i = P$ for all bases $i = 1, \dots M$, the SINR for user j is

$$W_j = \frac{G_{i_j j}}{\sum_{k \in \mathcal{B}: k \neq j} G_{i_k j}} \ . \qquad (2)$$

In order to ensure acceptable signal at a user's receiver, the SINR must exceed a certain threshold γ.

B. Modulation level

Each user i has bit rate requirements r_i (in bits/sec), which must be satisfied by the resource assignment algorithm. These requirements are translated into a number of bits x_i transmitted in a carrier frame, so that $x_i = r_i T_f$. We assume that x_i is a priori known for each user i. Although the allocation is performed here on a frame basis, the algorithm is also applicable when user requirements are available over larger time intervals, e.g. several successive frames, which would be easier to implement in a real system.

To achieve rate requirements, a user i is assigned a number of channels (timeslots) n_i, a modulation level b_i (bits/symbol) and a symbol rate s_i (symbols/sec) for transmission. The transmission parameters are selected from a finite L-element set $\mathcal{M}$ of available constellations and a finite set of available symbol rates respectively. Depending on processing capabilities of the system and implementation complexity, the same or different modulation levels and symbol rates can be assigned in different channels of a user. In our study, we assume that a fixed number of symbols, K, are transmitted in a timeslot duration. In other words, symbol rate is assumed to be constant and identical for all users, so that symbol rate adaptation is not an issue.

When modulation level b_i is fixed for all n_i channels of user i, we have

$$r_i = K \frac{1}{T_f} b_i n_i \ , \qquad (3)$$

and when different modulation levels are utilized in different channels of user i, we have

$$r_i = K \frac{1}{T_f} \sum_{\ell=1}^{L} b_\ell n_{i,\ell} \ , \qquad (4)$$

where $n_{i,\ell}$ is the number of timeslots of user i, in which modulation level $b_\ell \in \mathcal{M}$ is assigned. In our algorithm, we adopt the latter approach, namely we allow the assignment of different modulation levels in different channels of a user.

In order to maintain a constant BER for a user regardless of the quality of the channel, different modulation levels can be employed for different SINR values. Each modulation level $b_j \in \mathcal{M}$ demonstrates different amount of robustness to interference and therefore it can be mapped to a SINR threshold value γ_j through an one-to-one strictly increasing function f, such that $\gamma_j = f(b_j)$. Higher modulation levels are more sensitive to interference and are thus mapped to higher SINR thresholds, which tend to be violated easier in the event of channel errors.

Although the utilization of a TDMA/TDD channel access scheme is implied in this study, the principles of the proposed algorithms can be extended to other multiple access and signaling schemes with orthogonal channels. For example, in a network which supports OFDMA signaling, the orthogonal channels are essentially the subcarriers over which the information symbols of users are transmitted. A user may utilize several subcarriers in order to satisfy the rate requirements. An additional restriction here is that the assigned powers of subcarriers must satisfy certain constraints, which reflect transmitter/receiver hardware limitations. In a CDMA-based system, the orthogonal channels are parallelized to the orthogonal signature sequences, that constitute the codes to be allocated to users.

III. Resource Allocation and Modulation Control

A. Problem formulation

Each user of a base station receives interference from neighboring bases that utilize the same channel for transmission to other users. The amount of interference that can be tolerated by a user i is determined by the user's SINR threshold γ_i and consequently by the assigned modulation level b_i. The number of channels which are utilized by a user is also dependent on the modulation level.

When a high modulation level is assigned to a user in a channel, the throughput for that user is increased, since more bits are trasmitted in the channel. If high modulation levels are assigned for every channel of this user, the user will occupy fewer channels in order to satisfy the rate requirements. As a result, more users can be accomodated in the system and capacity is increased. However, the assignment of high modulation levels does not allow high resource reuse, i.e. not many users can share the same channel, since these modulation levels are more vulnerable to interference. To avoid cochannel interference, distinct channels must be utilized as a rule. From that point of view, high modulation does not contribute to capacity enhancement. On the other hand, a low modulation scheme implies that a small number of user bits is transmitted in a channel. A user with low modulation levels consumes more resources to satisfy the requirements and thus fewer users can be accomodated in the system. However, a low modulation level allows greater channel reuse by allowing more users to be "packed" in the same channel, since it is more robust to interference. Therefore, low modulation may increase system capacity, if viewed from that aspect.

Clearly, there exists a tradeoff between attainable throughput per channel and degree of resource (channel) reuse. The question that arises is how can modulation level assignment and channel allocation be performed jointly, so as to achieve high resource reuse and augmented throughput per channel and ultimately increase system capacity. In other words, we want to identify the set of cochannel users which achieves the maximum total throughput for every channel. Ideally, we would like to assign the highest possible modulation level to users and reuse the same channel for as many users as possible. This can be achieved if serving base stations are sufficiently far, so that their transmissions do not interfere with each other. However, if the locations of users and bases are such that cochannel interference is an issue, then resource reuse may be feasible only for a small subset of users and at certain modulation levels. In that case, users will be assigned either different channels and high modulation levels, or common channels and lower modulation levels, depending on the throughput gains of each policy.

We address the problem of resource allocation with modulation level and transmission power control in order to enhance system capacity and we propose a centralized algorithm to achieve this goal. The main idea of the algorithm is the following: for every available channel in the system, we allow the assignment of as many users as possible, performing simultaneously modulation level adaptation and power control, whenever the latter is allowed. The ultimate objective is to find the set of cochannel users that yields the maximum aggregate throughput in a channel. Since rate requirements of users are given, maximization of the aggregate throughput per channel is equivalent to minimization of the required number of channels to satisfy all users.

B. Rationale of the proposed algorithm

Before proceeding with the description of the algorithm, we state the motivation and present the main parameters and heuristics that are utilized. We first consider the case when power control is not involved.

Fix attention to a single channel. The set of cochannel users has cardinality at most M, since at most one user from each base station can be included in the channel. The identification of the set of cochannel users which yields the maximum aggregate throughput for this channel is a hard optimization problem. It first involves the selection of a particular user (if any) from each base station. Once the cochannel set is determined, the maximum sustainable modulation level must be obtained for each user. The difficulty lies in the fact that this modulation level of a user depends on the number and identities of the other base stations transmitting to users in the cochannel set, i.e. it depends on the cochannel set itself.

Let us assume for simplicity that each base station offers coverage to $S = N/M$ distinct users, so that a total of N users exist in the system. In particular, let $S_i = \{(i-1)S+1, (i-1)S+2, \ldots, iS\}$ denote the set of indices of users in base i, for $i = 1, \ldots, M$. An assignment of users in the cochannel set is specified by a vector $[\alpha_1, \alpha_2, \ldots, \alpha_M]$, where $\alpha_i \in S_i \cup \{0\}$ denotes the selected user (if any) from base i, that is included in the cochannel set. If $\alpha_i = 0$, no user is selected from base i. Clearly, there exist $(S+1)^M$ possible assignments. Let $\mathcal{K}$ denote the set of all user assignments. We can number the assignments as $k = 1, 2, \ldots$ and associate assignment k with the assignment vector $[\alpha_1(k), \alpha_2(k), \ldots, \alpha_M(k)]$. Then the problem of identifying the cochannel set of users that entails the maximum throughput can be formally stated as follows:

$$\max_{k \in \mathcal{K}} \sum_{i=1}^{M} b_{\alpha_i(k)} \ , \tag{5}$$

subject to:

$$W_{\alpha_i(k)} = \frac{G_{i\alpha_i(k)}}{\sum_{j=1, j\neq i}^{M} G_{j\alpha_i(k)}} \geq \gamma_{\alpha_i(k)}, \ \ \forall i \ \text{ s.t. } \ \alpha_i(k) \neq 0 \ , \tag{6}$$

where $b_{\alpha_i(k)}$ is the maximum achievable modulation level for user $\alpha_i(k)$, which is selected from set S_i according to assignment $k \in \mathcal{K}$ and $\gamma_{\alpha_i(k)}$ is the SINR threshold for that user, which depends on the modulation level.

Once an assignment $\hat{k}$ is given, the maximum modulation level $b^*_{\alpha_i(\hat{k})}$ can be found for all i. Assuming that each modulation level b is mapped to a SINR threshold γ through function f, so that $\gamma = f(b)$, we have

$$b^*_{\alpha_i(\hat{k})} = \max\left\{\beta_m \in \mathcal{M} : W_{\alpha_i(\hat{k})} \geq f(\beta_m)\right\} , \tag{7}$$

and the maximum aggregate throughput per channel is the sum of throughputs of the individual users. Since the enumeration of all user assignments is of exponential complexity, it is desirable to design a heuristic algorithm to construct the cochannel set of users in a sequential manner and obtain a high total throughput per channel.

C. Description of the proposed algorithm

The key idea of the algorithm is to "pack" as many users as possible in a channel, while enabling each user to achieve high throughput in it, i.e. use high modulation level. The order in which users are inserted in the channel is crucial: since the modulation level of a user is related to the amount of tolerable interference from other cochannel users, this interference must be kept to a minimum during the insertion procedure.

For a channel ℓ and a user m, we construct a *Signal-Interference related Factor (SIF)* $F_{\ell,m}$ with respect to the tentative assignment of user m in channel ℓ. A user should be inserted in a channel, if it is located close to the serving base, so that the strong received signal results in a high SINR and therefore a high modulation level. In addition, we consider a measure $I_{\ell,m}$ of the interference caused by base station i_m of user m to users that are already assigned to channel ℓ, as well as of the interference caused to user m from base stations transmitting to other users in the channel. We define the SIF $F_{\ell,m}$ as follows,

$$F_{\ell,m} = \frac{G_{i_m m}}{I_{\ell,m}} \ , \tag{8}$$

where

$$I_{\ell,m} = \max\left\{\sum_{n \in U^\ell} G_{i_m n}, \sum_{j \in B^\ell} G_{i_j m}\right\} , \tag{9}$$

where U^{ℓ} is the set of users which are already assigned to channel ℓ and B^{ℓ} is the set of neighboring base stations that transmit to users in channel ℓ and cause interference to user m. Among all candidate users, we would like to assign the user that receives a strong signal and causes or receives the minimum interference in the channel. This is accomplished by selecting the user with the highest SIF factor. Note that in the first step of the algorithm, when the channel is empty, the SIF factor for a user m is $F_{\ell,m} = G_{i_m m}$. This means that the first user to be inserted in the channel is the one with the strongest received signal.

Assume now that user m is tentatively inserted in the channel. Upon insertion, the SINR threshold of m may be violated because of the interference from other bases that transmit to users already assigned in the channel. It is also possible that SINR thresholds of some already existing users are violated by the insertion of this new user. In that case, users may coexist in the same channel, if we reduce the modulation levels of one or more users, so as to render them more robust to interference. The expense is then that user throughput for that channel is decreased. The addition of a user in the channel is beneficial if the decrease in channel throughput because of violated users is less than the throughput contribution of the new user. If the amount of induced interference of this tentative insertion is very high, the resulting channel throughput after the insertion may be lower than before. The coexistence of all users in the channel may also be infeasible even with the lowest modulation levels. Therefore, a user is eligible for insertion in the channel if channel throughput is incremented. In fact, *the most desirable user is the one for which the throughput increase is maximized.*

In order to formalize these considerations, for a channel ℓ and user m, we define $b^*_{\ell,m}$ to be the maximum modulation level of user m, so that the SINR requirements of this user are satisfied upon insertion in channel ℓ. Let $V_{\ell,m}$ denote the set of already assigned users to channel ℓ, for which the SINR constraints are violated with the addition of user m. For each user $k \in V_{\ell,m}$, let b^0_k be the modulation level before insertion of user m and b^*_k be the maximum modulation level for which the SINR threshold of user k is satisfied, after user m is inserted. For channel ℓ and user m, define the *Incremental Throughput Factor (ITF)* $T_{\ell,m}$ as follows,

$$T_{\ell,m} = b^*_{\ell,m} + \sum_{k \in V_{\ell,m}} \left(b^*_k - b^0_k\right). \tag{10}$$

Clearly, a user with high ITF factor is preferable for assignment in the channel, because channel throughput is increased. Since the inclusion of a user must not reduce the already achieved throughput of the channel, the assignment algorithm should terminate when $T_{\ell,n} < 0$ for all remaining users n. We note that if the assignment of user m in channel ℓ is infeasible even if the lowest modulation level is used for all users, then $T_{\ell,m}$ is set to $-\infty$ by convention. If m is the first user to be inserted in ℓ, then $T_{\ell,m} = b_L$.

Efficient allocation in a channel pertains to inserting users which cause the least interference to other users in the channel, receive the least interference from them and have the maximum contribution in throughput enhancement. To capture this objective, we define the *Channel Preference Factor* (CPF) $P_{\ell,m}$ for each channel ℓ and user m as,

$$P_{\ell,m} = F_{\ell,m} \cdot T_{\ell,m} \ . \tag{11}$$

Thus, among users which cause or receive the same amount of interference, the one that yields the greatest throughput enhancement is preferable to join the channel. Moreover, among users which cause the same increase in throughput, the user with the smallest amount of received or induced interference is inserted in the channel.

The algorithm considers the first available channel, selects the user with the maximum CPF factor from the list of candidate users and inserts the user in the channel. Candidate users must be served by bases different than the ones serving users in the channel. After every assignment, the CPF factors $P_{\ell,m}$ of candidate users are updated and the procedure is repeated until ITF factors $T_{\ell,m} < 0$ for all users m in the list of candidates, or until the list is empty.

After the assignment for a channel ℓ is completed, the same assignment is replicated for a number of consecutive channels D_{ℓ}, starting from channel $\ell + 1$, until the rate requirements of at least one user have been fulfilled. The number of assignment repetitions is

$$D_{\ell} = \min_{m \in U^{\ell}} \left\lceil \frac{r_m T_f}{K b^{\ell}_m} \right\rceil \ , \tag{12}$$

where $b^{\ell}_m \in \mathcal{M}$ is the modulation level of a user m in channel ℓ. This repetition of assignments increases the efficiency of the algorithm. The main steps of the algorithm are outlined as follows:

ALGORITHM A

- **STEP 1** : Consider the first available channel ℓ. Initially the list of candidates $\mathcal{L}$ includes all users.
- **STEP 2** : Compute the CPF factors $P_{\ell,m}$ for ℓ and users m in list $\mathcal{L}$.
- **STEP 3** : Select user $m^* \in \mathcal{L}$ with the maximum CPF factor and assign it to the channel. Remove user m^* and all users served by base i_{m^*} from $\mathcal{L}$.
- **STEP 4** : Update the CPFs of users in list $\mathcal{L}$.
- **STEP 5** : If the list $\mathcal{L}$ is empty or $T_{\ell,m} < 0$, $\forall\, m \in \mathcal{L}$, go to Step 6, otherwise go to Step 3.
- **STEP 6** : The assignment procedure for one channel is completed. Apply the same user assignment to D_{ℓ} channels, as in (12), until requirements of one user are satisfied. Update remaining rate requirements for users.
- **STEP 7** : Consider the next available channel and repeat the algorithm from Step 1, until requirements of all users are satisfied.

The complexity of the assignment algorithm for one channel in a system with M base stations, N users and L available modulation levels is $O\left(LNM^2\right)$. In the end, all users are assigned modulation levels and channels, so as to satisfy their rate requirements. In general, different modulation levels are used in different channels of a user. However, for users whose requirements are first satisfied in Step 6 above, the same modulation is used in all channels.

IV. RESOURCE ALLOCATION WITH MODULATION AND POWER CONTROL

In the previous section we presented an algorithm that achieves high channel throughput by performing jointly channel assignment and modulation control. While modulation level control can increase user robustness to interference and facilitate resource reuse, it does not alleviate the amount of cochannel interference itself. An appropriate base station transmission power control in conjunction with modulation level adaptation can reduce cochannel interference and provide further improvements in channel reuse and throughput.

A. Problem formulation

Consider an assignment $k \in \mathcal{K}$ of n users in channel ℓ, with $n \leq M$. Then, the path gain matrix $\mathbf{G} = \{G_{ij}\}$ for this assignment will be a $n \times n$ square matrix. For ease of notation, let G_{ij} be the path gain from base i to user j, with $j \in \{1, 2, \ldots, n\}$ and $i \in \{i_1, i_2, \ldots, i_n\}$. Let b_j be the modulation level of user j and $\gamma_j = f(b_j)$ be the SINR threshold. Let $\mathbf{b} = (b_1, b_2, \ldots, b_n)$ and $\gamma = (\gamma_1, \gamma_2, \ldots, \gamma_n)$ denote the modulation level and SINR threshold vectors. Define the base station transmission power vector $\mathbf{P} = (P_{i_1}, P_{i_2}, \ldots, P_{i_n}) \equiv (P_1, P_2, \ldots, P_n)$. The SINR for user j is given by (1) and the SINR constraints are satisfied if

$$W_j \geq \gamma_j, \ \ \forall j \in U^\ell \ . \tag{13}$$

A modulation vector $\mathbf{b}$ is said to be *achievable* in the cochannel set of the n users if there exists a power vector $\mathbf{P}$, such that the SINR constraints for all n users in the channel are satisfied. Condition (13) is written as

$$P_j \geq \sum_{i=1}^{n} \frac{\gamma_j}{1+\gamma_j} P_i Z_{ij}, \ \ \forall j \in U^\ell \ , \tag{14}$$

where $Z_{ij} = G_{ij}/G_{jj}$. In matrix form we have,

$$\mathbf{P} \geq \mathbf{P}\tilde{\mathbf{Z}} \ , \tag{15}$$

where

$$\tilde{\mathbf{Z}} = \left\{ \tilde{Z}_{ij} \right\} \ \text{ and } \ \tilde{Z}_{ij} = \frac{\gamma_j}{1+\gamma_j} Z_{ij} \ . \tag{16}$$

In [7], the problem of deriving the maximum achievable SINR threshold γ^* for a cochannel set of users with one SINR threshold was studied. It was shown that,

$$\gamma^* = \frac{1}{\lambda^* - 1} \ , \tag{17}$$

where λ^* is the largest real eigenvalue of matrix $\mathbf{Z}$. The power vector $\mathbf{P}^*$ achieving this maximum SINR is the eigenvector of $\mathbf{Z}$ corresponding to eigenvalue λ^*.

In our case, the problem of checking whether a given modulation vector $\mathbf{b}$ is achievable for a cochannel set of users is identical to that of finding the maximum positive eigenvalue of matrix $\tilde{\mathbf{Z}}$. Since $\tilde{\mathbf{Z}}$ is a non-negative matrix, it has exactly one real positive eigenvalue λ^*, for which the corresponding eigenvector is positive. Therefore, if $\lambda^* \leq 1$, then inequality (15) holds and the modulation vector $\mathbf{b}$ is achievable.

B. Description of Modulation and Power Control Algorithm

Consider again a single channel ℓ. The rationale for the algorithm of the previous section is applicable here with a significant modification: we want to identify the cochannel set of users with the maximum total throughput, where the modulation level vector $\mathbf{b}^*$ must be *achievable* through a transmission power vector $\mathbf{P}^*$. The number of possible assignments is $(S+1)^M$ and for an assignment $k \in \mathcal{K}$ there are $O(L^M)$ modulation vectors. However, even when an assignment $\hat{k}$ is given, the determination of an achievable modulation vector that yields the maximum aggregate throughput is not straightforward.

The joint adaptation of modulation level and power is performed for each channel ℓ separately. We begin by considering the maximum modulation level and insert user m with the maximum $F_{\ell,m}$ factor. Thus, the criterion for inserting a user is merely the induced and received interference. The feasibility of a cochannel set of users without power control is first examined. If SINR requirements are not satisfied, then power control is activated. The problem of testing the achievability of a modulation vector through power control for a set of cochannel users is identical to testing whether $\lambda^* \leq 1$ holds, where λ^* is the maximum eigenvalue of the modified path gain matrix $\tilde{\mathbf{Z}}$. After all candidate users are examined, modulation level is decreased and the same procedure is repeated for all candidate users, until all available modulation levels are exhausted. Note that reassignments of modulation levels for users in the channel are not considered as in Algorithm A, since the complexity of the algorithm is increased. The main steps of the Modulation and Power Control algorithm are as follows:

ALGORITHM B

- **STEP 1** : Consider the first available channel ℓ and the maximum modulation level b_L. Initially the list of candidates $\mathcal{L}$ includes all users.
- **STEP 2** : Compute the SIF preference factors $F_{\ell,m}$ for all users m in list $\mathcal{L}$.
- **STEP 3** : Select user m^* with the maximum SIF factor and tentatively assign it to the channel.
- **STEP 4** : Check if SINRs of users are satisfied without power control.
- **STEP 4.A** : If they are satisfied, assign user m^* to channel. Remove user m^* and all users served by base i_{m^*} from list $\mathcal{L}$.
- **STEP 4.B** : If SINRs are not satisfied, activate power control. Find a power vector $\mathbf{P}^*$ (if any), so that the current modulation vector is achievable. If such a power vector is found, assign user m^* to channel. Remove user m^* and all users served by base i_{m^*} from list $\mathcal{L}$.
- **STEP 5** : Update the SIF factors of users in list $\mathcal{L}$.
- **STEP 6** : If all candidates are examined, go to Step 7, otherwise go to Step 2.
- **STEP 7** : Reduce modulation to the next lower level. If all available modulation levels are exhausted go to Step 8, otherwise go to Step 3.
- **STEP 8** : The assignment procedure for one channel is

completed. Apply the same user assignment to D_ℓ channels, as in (12), until the requirements of one user are fulfilled. Update remaining rate requirements for users.

- **STEP 9** : Consider the next available channel and repeat from Step 1, until requirements of all users are satisfied.

The computationally intensive part of the algorithm is the determination of the eigenvalues of the $n \times n$ matrix $\mathbf{G}$ for a set of n cochannel users. This is known to be of complexity $O(n^3)$. For M base stations, N users and L modulation levels, the complexity of the algorithm for assignment in one channel is $O\left(LN^2M^3\right)$.

V. SOME SIMPLE SPECIAL CASES

In this section we consider some simple cases of modulation level and power control and derive simplified versions of the proposed algorithms. The performance criterion is again the number of utilized channels. Consider a system with two base stations. Let U_i be the set of users assigned to base i, for $i = 1, 2$. Then, at most two users can share the same channel. To minimize the number of channels required for all users, one has to identify the maximum number of pairs of users from different bases, so that each pair shares a channel. The problem is equivalent to a maximum matching problem on an appropriately defined graph. In the following, we consider some instances of this problem.

A. One modulation level

Assume that a single modulation level b with SINR threshold γ is used for all users. The number of channels for user i with rate requirements r_i is,

$$n_i = \left\lceil \frac{r_i T_f}{Kb} \right\rceil \ . \tag{18}$$

Construct a bipartite graph $G = (U \cup V, E)$ as follows. Create one node for each required channel of a user. Thus, $|U| = \sum_{i \in U_1} n_i$ and $|V| = \sum_{i \in U_2} n_i$. An edge (i, j) is added between nodes $i \in U$ and $j \in V$ (denoting channels of users $\alpha \in U_1$ and $\beta \in U_2$ respectively) if the SINR thresholds of these users are satisfied, i.e. if

$$\min\left\{\frac{G_{1\alpha}}{G_{2\alpha}}, \frac{G_{2\beta}}{G_{1\beta}}\right\} \geq \gamma, \tag{19}$$

so that these users can coexist in the same channel. 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. Every edge in $\mathcal{M}$ is called a matched edge. A maximum matching $\mathcal{M}^*$ is a matching of maximum cardinality. As an extension to a theorem stated in [17], we have that: For one modulation level, the minimum number of channels required to accomodate users belonging to one of two base stations is equal to the cardinality of a maximum matching in the corresponding bipartite graph plus the number of nodes that are not incident to a matched edge.

The optimal assignment is as follows. Each edge in $\mathcal{M}^*$ corresponds to two channels of a cochannel pair of users. Assign each such pair to a separate channel. Then, for each user that corresponds to a node that is not incident to a matched edge, consider a separate channel and assign the user to it.

B. Multiple modulation levels

Assume now that multiple modulation levels $b_1, b_2, \ldots b_L$ are used. Then, the exact number of required channels for a user is not known a priori and therefore the maximum matching method is not applicable. Instead, the modulation level assignment will be performed on a per channel basis, with a procedure similar to that presented in section III.

The goal is to create cochannel sets with pairs of users that use high modulation levels. For each pair of users (i, j), with $i \in U_1$ and $j \in U_2$, we define a weight $w(i, j) = b_i + b_j$, where b_i, b_j are the maximum modulation levels of users i and j, such that they can coexist in a channel. In other words,

$$b_i = \max\left\{\beta_m \in \mathcal{M} : \frac{G_{1i}}{G_{2i}} \geq f(\beta_m)\right\} \tag{20}$$

$$b_j = \max\left\{\beta_m \in \mathcal{M} : \frac{G_{2j}}{G_{1j}} \geq f(\beta_m)\right\} \ .$$

For each user k we define weights $w(k) = b_L$, since the maximum modulation level is used when a single user occupies a channel. Clearly, assignment of one user with modulation b_L to a channel is more beneficial than assignment of two users i and j, if interference between i and j causes modulation levels b_i and b_j to be such that $b_i + b_j < b_L$.

The weights $w(k)$ for user k and $w(i, j)$ for a pair of users (i, j) are ordered together in non-increasing order. The algorithm selects the pair of users (i^*, j^*) (or single user k^*) with the maximum weights $w(i^*, j^*)$ (or $w(k^*)$) and assigns it to a channel. Let a pair of users (i^*, j^*) be selected. The same assignment is replicated for $D = \min\left\{\left\lceil \frac{r_{i^*} T_f}{K b_{i^*}} \right\rceil, \left\lceil \frac{r_{j^*} T_f}{K b_{j^*}} \right\rceil\right\}$ consecutive channels, until requirements of i^* (or j^*) are satisfied. Then, rate requirements are updated and all pairs of users containing i^* (or j^*) are removed from the list. The next available channel is then selected and the procedure is repeated with the next ordered pair of users (or single user) until all users achieve their rates.

C. Multiple modulation levels and power control

Consider now the more general form of the problem, where multiple modulation levels $b_1, b_2, \ldots b_L$ are used and base transmission powers P_1 and P_2 are adjustable. The idea is again to create cochannel sets with pairs of users that use high modulation levels. As in the previous problem, for a user k we define a weight $w(k) = b_L$, accounting for the case when k is assigned alone in a channel without power control. For each pair of users (i, j) with $i \in U_1$ and $j \in U_2$, we define a weight $w(i, j) = b_i + b_j$, where b_i, b_j are the maximum *achievable* modulation levels of users i and j, i.e. the maximum modulation levels for which there exist powers P_1 and P_2, so that users can coexist in a channel. Thus,

$$b_i = \max\left\{\beta_m \in \mathcal{M} : \exists\, P_1, P_2 : \frac{G_{1i} P_1}{G_{2i} P_2} \geq f(\beta_m)\right\} \tag{21}$$

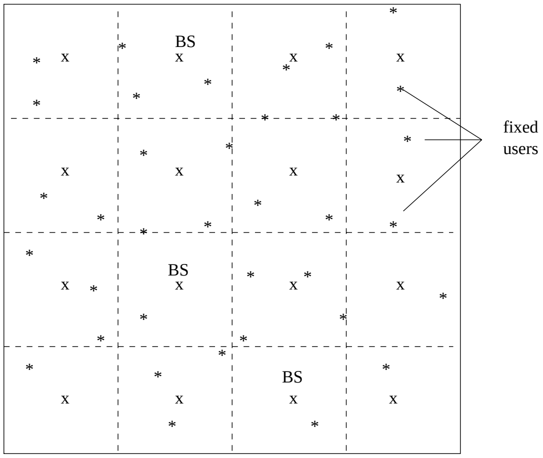

Fig. 1. The simulated wireless network.

$$b_j = \max \left\{ \beta_m \in \mathcal{M} : \exists\, P_1, P_2 : \frac{G_{2j} P_2}{G_{1j} P_1} \geq f(\beta_m) \right\} ,$$

or, in a more compact form,

$$\frac{G_{1i}}{G_{2i}} \cdot \frac{G_{2j}}{G_{1j}} \geq f(b_i) f(b_j) \tag{22}$$

The assignment is then achieved by an algorithm similar to that described in the previous subsection.

VI. NUMERICAL RESULTS

A. Simulation settings

We consider a cellular network in an area of 8 × 8 km with 16 base stations, as illustrated in Figure 1. Each base is located in the center of a square grid that represents a cell. The distance between consecutive bases in the same row or column is 2 km. Users are located in fixed but random positions, uniformly distributed in the area, and each user establishes connection with the closest base. In order to avoid edge effects, a cell wraparound technique is used. System resources consist of a single carrier which is available in all cells. The carrier is divided into downstream and upstream portions, as in a TDMA/TDD scheme and consists of timeslots. The propagation model assumes operation in a suburban environment and takes into consideration path loss and shadowing [18]. The received signal (in dB) at distance d from the base station is

$$L(d) = L(d_0) + 10\kappa \log \frac{d}{d_0} \tag{23}$$

where $d_0 = 10\,m$ is used as a reference point in measurements ($L(d_0) = 0$ dB) and κ is the path loss exponent, which is set to 4. Shadow fading for each user is modeled as an independent log-normal random variable with standard deviation $\sigma = 10$dB, while multipath fading is not simulated. The path gain matrix $\mathbf{G}$ is constructed by applying this model for each pair of base station and user.

A target BER of 10^{-3} is assumed for users. For an M-QAM constellation in an AWGN environment, the BER performance is approximated by [19]

$$BER = 0.2 \exp^{[-1.5\gamma/(M-1)]} , \tag{24}$$

where γ is the SINR. We find that the minimum SINR value for modulation level M is

$$\gamma = -\frac{M-1}{1.5} \ln(5\, BER) . \tag{25}$$

This relation determines the SINR threshold for a particular modulation level.

B. Comparative results

The main goal of the simulations is to study the performance of different adaptive transmission techniques. The following schemes are evaluated:

- Resource allocation with adaptive modulation. This is the proposed algorithm of section III. It refers to joint channel assignment and modulation level control, with the objective to maximize channel throughput.
- Resource allocation with adaptive modulation and power control. This algorithm was presented in section IV and includes joint consideration of channel assignment, modulation level adaptation and base station transmission power control to form the cochannel set of users.
- Resource allocation with power control and a fixed modulation level. This technique is the classical power control proposed by Zander in [7], and uses the concept of SINR balancing for cochannel users. The assignment of users in a channel is again performed in accordance to the induced/received interference criterion for comparison purposes.

The main performance criterion is the average throughput per channel. Results were obtained by averaging over carriers of all cells and over 100 random experiments with different user locations. Link conditions were assumed to be stationary for the duration of a frame, that is during the assignment procedure. Figure 2 illustrates the cumulative distribution function of the throughput per channel for each of the three methods above. When modulation control was considered, a scheme with six modulation levels was utilized, otherwise a fixed modulation level (the highest) was used. For a system with 16 base stations, the maximum achievable throughput per channel in perfect channel conditions is 96 bits, since at most one user per base station can be included in a channel. The power control scheme turns out to provide the lowest throughput per channel, whereas the performance of modulation control is significantly better. For example, consider a channel throughput value of 60 bits, which accounts for a percentage of 60% of channel utilization under certain interference limitations. With modulation level adaptation, more than half of the channels (about 54% of them) achieve or exceed this throughput, which is an indication that resources are utilized efficiently. Joint application of modulation and power control results in a small further improvement (approximately 58% of the channels reach or exceed the aforementioned throughput). Note that for a power control scheme, the same throughput is achieved by only 20% of the channels.

The best result in terms of throughput is therefore achieved by joint modulation and power control. However, the computational complexity of power control is significantly higher than that of modulation control. In a realistic system, base station power adaptation would require a large number of measurements and feedback information to appropriately adjust power level. Therefore, by following the design guidelines of the proposed algorithm, modulation level adaptation alone can be applied to increase system throughput and maintain complexity at a reasonable level.

Figure 3 shows the average throughput per channel as a function of the available number of modulation levels. When k modulation levels are utilized, the assumption is that these are $b_L, b_{L-1}, \ldots, b_{L-k+1}$, where b_L is the highest modulation level. Simulation results show that the enhancement of an adaptive modulation scheme with power control is beneficial only in the case when a small number (at most four) of modulation levels are used. Consider for example the case when one (the highest) modulation level is used, which can be applied in real systems, in order to increase system throughput. Joint modulation and power control can then achieve up to 55% more throughput than plain modulation control (note that the term "modulation control" in this case is redundant). Therefore, there is considerable throughput gain in a real system with a fixed modulation level and power control. In that case, however, this throughput improvement is counterbalanced by the amount of complexity of power control implementation. With the addition of the immediately lower modulation level, the throughput for the joint control approach is about 20% larger than that of simple modulation control. The addition of more lower modulation levels to the adaptive modulation scheme improves throughput performance further and makes it converge to that of joint modulation and power control. We also observe that the contribution of multiple modulation levels to system throughput increase is marginal.

In Figure 4, the throughput performance of the three adaptive schemes is shown as a function of the severity of the interference environment, which is reflected in the average SINR of all users. Random user positions were generated and the received useful signal and interference were measured, before the algorithm takes effect. A low SINR corresponds to users located far from base stations or users receiving high interference. Simulation results show that adaptive modulation alleviates the effect of interference and that throughput performance is remarkably better than the one achieved with power control. For instance, for an average SINR of 5 dB, the achieved throughput per channel for modulation control is double as the throughput for power control. This demostrates the fact that modulation adaptation can be very effective in intense interference environments. Power control alone cannot provide sufficiently good throughput, because of the involved SINR balancing concept, which is not applicable for cases of high interference. For milder interference conditions (i.e. higher SINR values), the difference in performance becomes less evident, since all algorithms combat interference and perform efficient resource assignment. Joint modulation and power control always achieves the highest throughput per channel and therefore the highest capacity in the system.

VII. Discussion

In this paper, we considered the problem of resource allocation with adaptation of modulation level and transmission power, with the objective to achieve high throughput under certain interference conditions. The determination of the optimal solution in terms of the amount of utilized resources is a hard optimization problem. In section V, simplified algorithms were devised for a system with two base stations, by identifying all pairs of users that can share a channel and selecting the pairs that achieve high channel throughput. In a network with many base stations and users, the corresponding task would be to identify all possible subsets of users that can share a channel and then consider all possible combinations of modulation levels of users in order to find the subset which results in maximum throughput per channel. Clearly, such a procedure becomes intractable for a large system. Therefore some heuristic algorithms along the lines of the simplified methods must be applied, so that their solution will approximate the optimal one and will provide performance bounds for more general algorithms.

Such a heuristic algorithm for resource allocation and modulation control is proposed in section III and is enhanced with power control in section IV. Simultaneous application of both adaptation schemes achieves the highest throughput per channel, while autonomous modulation control also performs remarkably well. The algorithms are centralized in the sense that base station coordination, data processing and required allocations are performed by a central agent. Thus, the amount of signaling information and processing load would be very high, particularly for a large system. Therefore, the proposed algorithms aim to provide an insight on accomplishment of such allocation methods, approximate performance bounds and create the baselines for the design of more general algorithms. An interesting topic for investigation would be to devise the distributed version of such algorithms, which would reduce the amount of coordination between bases and would be easier to implement in real time.

Although the proposed algorithms were studied for a TDMA/TDD channel access scheme, the basic principle can be applied in systems that support different signaling schemes, in which orthogonality of channels is implied. For example, in an OFDMA-based system with orthogonal subcarriers and users with certain rate requirements, users transmit information symbols by using a certain number of subcarriers in parallel. The presented idea can be applied here to perform user allocation with modulation level and power control per subcarrier, so as to maximize subcarrier reuse and system capacity. However, some algorithmic arguments may need to be reconsidered, due to the subcarrier power constraints, that reflect transmitter and receiver hardware limitations. In a CDMA system with orthogonal signature sequences (codes), users achieve their rates by using one or more codes. Interference occurs between users that share the same code and the SINR of a user depends on the user's processing gain (namely transmission symbol rate, if the chip rate is fixed) and power level. The equivalent problem would be to assign codes to users and perform processing gain and transmission power adaptation on a per code basis in order to improve system capacity.

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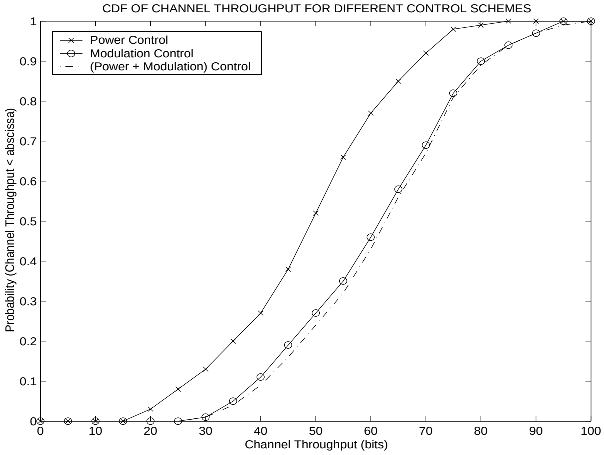

Fig. 2. Throughput comparison for different adaptive transmission techniques.

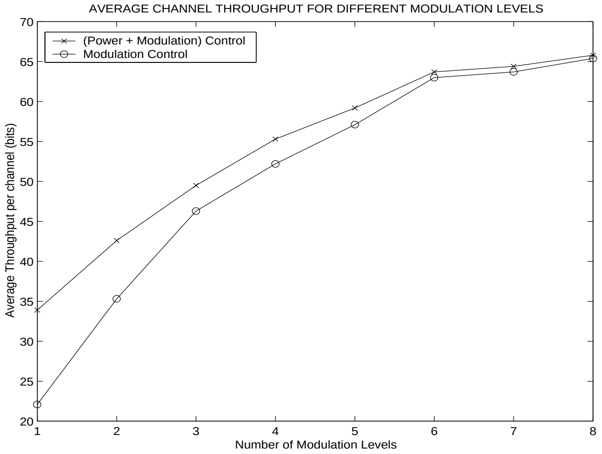

Fig. 3. Average channel throughput for different number of available modulation levels.

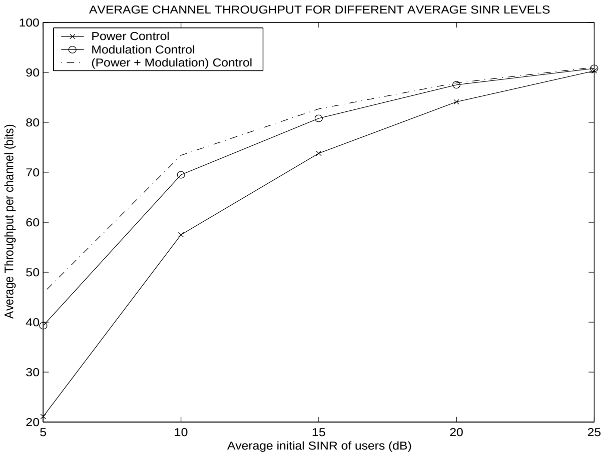

Fig. 4. Throughput comparison for different initial interference conditions (initial SINR values).