AN ALGORITHM FOR CROSS-LAYER SUBCARRIER AND POWER ALLOCATION IN CELLULAR NETWORKS

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ABSTRACT

Inter-cell interference is a major challenge in multi-user multi-carrier cellular networks, especially for cells with overlapping coverage. Several subcarrier and power allocation algorithms have been developed to deal with this problem. However, they focus on maximizing data rates using only physical layer information, disregarding upper layer information like the queue backlogs. Assigning subcarriers to the users based only on physical layer information like the channel conditions maximizes data rates, but may lead to network instability. To tackle this problem, we propose a cross-layer subcarrier and power allocation algorithm that uses physical layer information to reduce inter-cell interference and upper layer information to stabilize the network. Furthermore, our approach achieves a larger rate region than the baseline approach by protecting users in neighboring cells.

Index Terms— Cross-layer, network stability, inter-cell interference

1. INTRODUCTION

Inter-cell interference is a major challenge in cellular networks, especially for cells with overlapping coverage [1, 2]. In multi-carrier cellular networks, multiple users can avoid interference within the cell by having a disjoint set of subcarriers. Still, neighboring cells need to share the bandwidth at the cost of creating inter-cell interference.

Subcarrier and power allocation has been extensively studied to reduce the interference caused on neighboring cells. For example, in the DSL context, a set of power allocation algorithms based on iterative water-filling (IWF) [3] has been proposed in [4] and [5]. They introduce the concept of protection to a reference user suffering interference from a contiguous transmission. In [6, 7] this idea has been used in cellular networks to protect users from neighboring cells. Joint subcarrier and power allocation algorithms that are effective in dealing with inter-cell interference have been presented in [8–10]. Apart from a few exceptions like in [11] for DSL, all these solutions aim at maximizing the data rates using only physical layer information, disregarding upper layer information like the queue backlogs, which is actually more important to assess the end-users satisfaction. It is well known that serving users based only on physical layer information like the channel conditions maximizes the data rates of the served users. However this policy leads to network instability by allowing the queue backlog of non-served users to increase monotonically.

Motivated by this, we look into how the end-user experience can be improved by combining physical layer information with upper layer information. Therefore, we propose a cross-layer subcarrier and power allocation algorithm that uses physical layer information to protect users in neighboring cells from inter-cell interference and upper layer information to stabilize the network.

The paper is organized as follows. Section 2 describes the system model. Section 3 presents the proposed algorithm. Section 4 presents the performance evaluation of the proposed algorithm. Finally section 5 draws some conclusions.

2. SYSTEM MODEL

Consider a cellular sytem composed of two base stations[1] with overlapping coverage as seen in Fig. 1, using a multi-carrier transmission scheme such as orthogonal frequency division multiplexing (OFDM) and sharing the same bandwidth. This means that users within a cell are assigned a disjoint set of subcarriers, but users from neighboring cells can share subcarriers hence producing inter-cell interference. We consider a downlink transmission over K subcarriers to L users in each cell and that communication is done in time-slots.

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[1] A scenario with more base stations is subject of future work.

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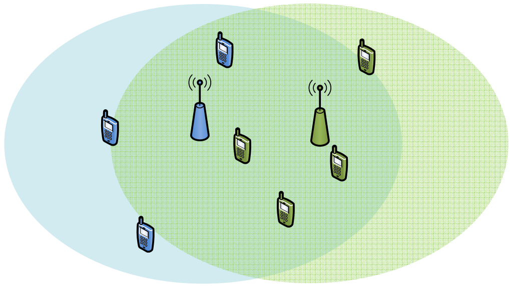

Fig. 1. System model with two base stations with overlapping coverages. The users color indicates the base station to which they are connected.

Assume that user i is connected to base station b and has one queue. Packets arrive to the queue with an arrival rate $A^{i,b}(t)$ satisfying $E\{A^{i,b}(t)\} \leq R^{i,b}(t)$ for all i, where $R^{i,b}(t)$ represents the achievable data rate of user i connected to base station b at time t, hence the average packet arrivals are within the capacity region. Let $U^{i,b}(t)$ represent the queue backlog of user i connected to cell b in time-slot t such that the queueing dynamics satisfy:

$$U^{i,b}(t+1) = \max[U^{i,b}(t) - R^{i,b}(t), 0] + A^{i,b}(t). \tag{1}$$

In every time-slot, each base station observes the queue backlog and channel conditions of each connected user and decides on the subcarrier and power allocation. Our goal is to allocate subcarriers and power in an efficient manner, while keeping the network stable.

2.1. Baseline Approach

The baseline approach is composed of a max-rate subcarrier allocation and an IWF power allocation. In a max-rate subcarrier allocation, a subcarrier is assigned to the user with the highest instantaneous channel gain, maximizing in this way the aggregate[1] data rate at the expense of serving only the users with the best channel conditions. This means that, from all the users, base station b assigns subcarrier k to the user with the largest channel gain in time-slot t such that

$$i^*(t) = \arg\max_i |h_k^{i,b}(t)|, \tag{2}$$

where $i^*(t)$ is the selected user in time-slot t on subcarrier k and $h_k^{i,b}(t)$ is the channel gain from base station b to user i on subcarrier k in time-slot t. For simplicity, we now disregard the time label as the following optimization is done per time-slot.

As a second step, an IWF power allocation is done considering the equivalent channel as selected by the max-rate subcarrier allocation algorithm. The IWF power allocation algorithm corresponds to maximizing the aggregate data rate in cell b under total power and spectral emission mask constraints based only on physical layer information:

$$\begin{aligned}\underset{p_k^b\ \forall k}{\text{maximize}}\quad & \sum_{i=1}^{L} R^{i,b}\\ \text{s.t.}\quad & \sum_{k=1}^{K} p_k^b \leq P^{b,\text{tot}}\\ & 0 \leq p_k^b \leq p_k^{b,\text{mask}}\ \forall k\end{aligned} \tag{3}$$

with

$$R^{i,b} = f_s \sum_{k=1}^{K} \delta_k^{i,b} \log_2\left(1 + \frac{|h_k^{i,b}|^2 p_k^b}{|h_k^{i,\bar{b}}|^2 p_k^{\bar{b}} + \sigma_k^i}\right), \tag{4}$$

where $R^{i,b}$ is the data rate of user i connected to cell b and $\delta_k^{i,b} = 1$ if subcarrier k is allocated to user i, i.e. if $i = i^*$ and $\delta_k^{i,b} = 0$ otherwise. Then f_s is the symbol rate, σ_k^i, p_k^b, $p_k^{\bar{b}}$, and $p_k^{b,\text{mask}}$ are the noise power received by user i, the transmit power of cell b and cell $\bar{b}$, and the spectral emission mask constraints of cell b on subcarrier k, respectively, and $h_k^{\bar{b}}$ is the channel gain from base station $\bar{b}$ to user i. The parameter $P^{b,\text{tot}}$ is the total power budget in cell b.

Using the corresponding Karush-Kuhn-Tucker (KKT) conditions, it can be shown that the transmit powers have a solution as follows

$$p_k^b = \left[\frac{f_s}{\log(2)\lambda} - \frac{|h_k^{i,\bar{b}}|^2 p_k^{\bar{b}} + \sigma_k^i}{|h_k^{i,b}|^2}\right]_0^{p_k^{b,\text{mask}}}, \tag{5}$$

where $[x]_a^b = \max(a, \min(x, b))$ and λ is the Lagrange multiplier that has to be adjusted (e.g. with bisection) to satisfy the total power constraint $P^{b,\text{tot}}$. The interference term $|h_k^{i,\bar{b}}|^2 p_k^{\bar{b}}$ is assumed to be known by cell b.

The advantage of IWF is its simplicity and the fact that it does not require information exchange between cells. However, each cell maximizes its own data rate in a greedy fashion by allocating power to those subcarriers with the best channel-to-interference-and-noise ratio, without considering the interference caused to the users in neighboring cells.

3. CROSS-LAYER SUBCARRIER AND POWER ALLOCATION

3.1. Subcarrier Allocation

One way of stabilizing the network is to reduce the aggregate queue backlog of all the users in the network. To this end, the proposed subcarrier allocation assigns subcarrier k to the user with the largest queue backlog in time-slot t such that:

$$i^*(t) = \arg\max_i \left[U^{i,b}(t)\right]. \tag{6}$$

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[1] The term aggregate refers to the sum of all the users in one cell.

For simplicity, we now disregard again the time label. The proposed subcarrier allocation stabilizes the network by giving priority to users having the largest queue backlogs. It is inspired on the Single-hop Dynamic Backpressure and Resource Allocation Algorithm, which stabilizes the network whenever the arrival rates lie within the capacity region of the network [14]. However, we apply it in this paper for subcarrier allocation in a multi-user network instead of a point-to-point link, and we use it in combination with the power allocation of section 3.2 to reduce inter-cell interference.

3.2. Power Allocation

The subcarrier allocation has an impact on the power allocation and hence on the interference generated to cell $\bar{b}$. Therefore, our goal is to protect the users of cell $\bar{b}$, while degrading as least as possible the data rate of users from cell b. Therefore, we propose the maximization of the aggregate data rate of users in cell b and users in cell $\bar{b}$:

$$\begin{aligned} \underset{p_k^b\ \forall k}{\text{maximize}} \quad & \sum_{i=1}^{L} R^{i,b} + \sum_{j=1}^{L} R^{j,\bar{b}} \\ \text{s.t.} \quad & \sum_{k=1}^{K} p_k^b \leq P^{b,\text{tot}} \\ & 0 \leq p_k^b \leq p_k^{b,\text{mask}}\ \forall k, \end{aligned} \tag{7}$$

where $R^{j,\bar{b}}$ refers to the data rate of the user j connected to cell $\bar{b}$. The aggregate data rates can be expanded as

$$\begin{aligned} R^{i,b} &= f_s W^{i,b} \sum_{k=1}^{K} \delta_k^{i,b} \log_2\left(1 + \frac{|h_k^{i,b}|^2 p_k^b}{|h_k^{i,\bar{b}}|^2 p_k^{\bar{b}} + \sigma_k^i}\right) \\ R^{j,\bar{b}} &= f_s W^{j,\bar{b}} \sum_{k=1}^{K} \delta_k^{j,b} \log_2\left(1 + \frac{|h_k^{j,\bar{b}}|^2 p_k^{\bar{b}}}{|h_k^{j,b}|^2 p_k^b + \sigma_k^j}\right), \end{aligned} \tag{8}$$

where $\delta_k^{j,b} = 1$ if subcarrier k is allocated to user j and $\delta_k^{j,b} = 0$ otherwise. We define $W^{i,b} = U^{i*,b}$ as the weight assigned to user i in cell b, which will be used in the power allocation algorithm of section 3.2, and $W^{j,\bar{b}}$ as the weight assigned to user j in cell $\bar{b}$. To avoid excessive information exchange between base stations, $W^{j,\bar{b}}$ can be assigned a fixed value for all users in cell $\bar{b}$ [7].

Applying the KKT stationarity condition to problem (7) on a per-subcarrier basis leads to

$$\begin{aligned} \forall k: \ & \frac{\frac{1}{\log(2)} W^{i,b} f_s |h_k^{i,b}|^2}{\left(|h_k^{i,b}|^2 p_k^b + |h_k^{i,\bar{b}}|^2 p_k^{\bar{b}} + \sigma_k^i\right)} \\ & - \frac{\frac{1}{\log(2)} W^{j,\bar{b}} f_s |h_k^{j,\bar{b}}|^2 p_k^{\bar{b}} |h_k^{j,b}|^2}{\left(|h_k^{j,b}|^2 p_k^b + \sigma_k^j\right)\left(|h_k^{j,\bar{b}}|^2 p_k^{\bar{b}} + |h_k^{j,b}|^2 p_k^b + \sigma_k^j\right)} - \lambda = 0. \end{aligned} \tag{9}$$

Then, by taking into account the KKT complementarity conditions, p_k^b can be computed as:

$$p_k^b = \left[\frac{W^{i,b}\frac{f_s}{\log(2)}}{\lambda + T_k} - \frac{|h_k^{i,\bar{b}}|^2 p_k^{\bar{b}} + \sigma_k^i}{|h_k^{i,b}|^2}\right]_0^{p_k^{b,\text{mask}}}, \tag{10}$$

where T_k is a penalty factor that reduces the interference to users in cell $\bar{b}$. It is defined as

$$T_k = \frac{W^{j,\bar{b}} f_s |h_k^{j,\bar{b}}|^2 p_k^{\bar{b}} |h_k^{j,b}|^2}{\log(2)\left(|h_k^{j,b}|^2 p_k^b + \sigma_k^j\right)\left(|h_k^{j,\bar{b}}|^2 p_k^{\bar{b}} + |h_k^{j,b}|^2 p_k^b + \sigma_k^j\right)}, \tag{11}$$

resulting in a fixed point equation as T_k depends on p_k^b. Setting T_k to zero will result in the IWF power allocation algorithm.

Our maximization problem is a nonconvex optimization problem for which a duality gap exists between the solution of (10) and the optimal solution. However, as the number of subcarriers increases, this duality gap goes to zero [12]. By adding to equation (10) a bisection search on the Lagrange multiplier to satisfy the total cell power constraint as well as the subcarrier allocation of section 3.1, we obtain Algorithm 1. The parameter η indicates the accuracy of the total power constraint, γ indicates the stopping criterion of the bisection search on λ in the case of an inactive total power constraint, and $\Lambda^{\max}$ is the maximum value for λ.

Algorithm 1

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Initialize $W^{i,b}$ according to the subcarrier allocation defined in section 3.1 and and $W^{j,\bar{b}} = 1$
Initialize $p_k^b = 0$
repeat
    $\lambda^{\min} = 0; \lambda^{\max} = \Lambda^{\max}$
    $\lambda = (\lambda^{\max} + \lambda^{\min})/2$
    while $|\sum_{k=1}^{K} p_k^b - P^{b,\text{tot}}| > \eta$ and $\lambda > \gamma$ do
        $\lambda = (\lambda^{\max} + \lambda^{\min})/2$
        for $k = 1 : \mathcal{K}$ do
            repeat
                Update $p_k^b$ in (10)
            until convergence
        end for
        if $\sum_{k=1}^{K} p_k^b > P^{b,\text{tot}}$ then
            $\lambda^{\min} = \lambda$
        else
            $\lambda^{\max} = \lambda$
        end if
    end while
until network convergence
```

By varying the value of $W^{i,b}$ from zero to the maximum value within the capacity region, while keeping a fixed value of $W^{j,\bar{b}}\ \forall j$, we generate a curve that trades off the aggregate data rates of both cells as seen in Fig. 2. Since IWF cannot provide this trade-off, the total power is tuned between 0 and $P^{b,\text{tot}}$ to obtain different operating points. In a scenario with overlapping cells, the performance of IWF is clearly degraded by the inter-cell interference, while the proposed cross-layer approach achieves a larger rate region for all operating points. This result highlighs the importance of providing some level of protection to users in cell $\bar{b}$ as proposed in our approach.

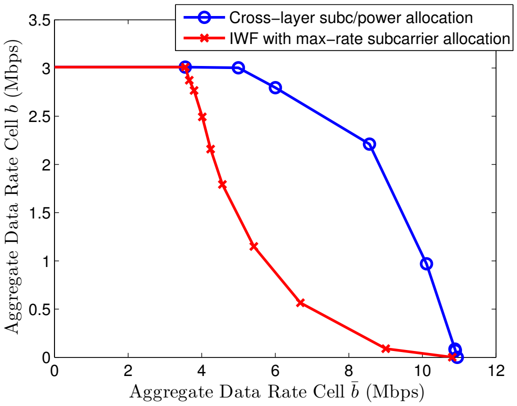

Fig. 2. Aggregate rate region for 2 overlapping cells with 10 users each and parameters from Table 1 averaged over multiple channel realizations.

3.3. Network Stability

Stability refers to the condition that the queue backlogs of all users in the system remain finite. This can be defined by the following Lemma:

Lemma 1. (Lyapunov Stability) The system is said to be stable if

$$\limsup_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \sum_{i=1}^{L} \mathrm{E}\{U^{i,b}(\tau)\} \leq \infty. \qquad (12)$$

When dealing with multi-user systems, stability is not achieved by simply serving any non-empty queue. Serving the shorter queue with the largest transmission rate leads to instability by monotonically increasing the queue backlog of the queues not served, even though this policy maximizes the data rate when all the queues are infinitely backlogged. One of the most commonly used tools to prove stability is the Lyapunov drift. The idea is to define a Lyapunov function as a scalar measure of all the queues in the network. If the drift is negative whenever the aggregate queue backlog is greater than a certain constant, then the system is stable. By defining the following quadratic Lyapunov function $Y(U)$

$$Y(U) = \sum_{i=1}^{L} U^{i,b}(t)^2, \qquad (13)$$

we can prove the stability of the network whenever the arrival rates $A^{i,b}(t)$ are independently and identically distributed (i.i.d.) over time-slots with mean inside the achievable rate region, i.e. $E\{A^{i,b}(t)\} \leq R^{i,b}(t)$. This was proven in [14] for point-to-point links, but a similar analysis can be used to prove stability in a multi-user multi-carrier cellular system. Due to space limitations, we limit to show the achieved stability through simulations in the next section.

Parameter	**Value**
System Bandwidth	5 MHz
Number of data subcarriers	200
η	10^{-6}
γ	10^{-6}
Λ^{max}	10^{8}
f_s	1.4 Gsymbols/s
Base station total transmit power	50dBm

Table 1. Simulation parameters.

4. PERFORMANCE EVALUATION

We evaluate our approach on a cellular network with two overlapping cells, and 10 users per cell with parameters from Table 1. As channel profile we use the 3GPP SCM channel model [13] with low mobility such that the channel conditions vary slowly between time-slots. The arrival of packets for each user occurs every time-slot and it is an i.i.d process with a mean inside the achievable rate region of Fig. 2.

We compare the performance of both cells by using the baseline approach presented in section 2.1 with full-power transmission and the proposed cross-layer approach presented in section 3. In Fig. 3 we measure the aggregate queue backlog of both cells. We can observe that only the proposed cross-layer approach is able to keep the network stable. Furthermore, it is able to increase the average data rate of the users in both cells compared to the baseline approach, especially that of the users in cell $\bar{b}$. This is because the proposed cross-layer approach is able to achieve a larger rate region by reducing inter-cell interference. This can be seen Fig. 4, which shows the instantaneous and the average data rates of cell b and cell $\bar{b}$ for both approaches.

5. CONCLUSIONS

In this paper we have proposed a cross-layer approach for subcarrier and power allocation in a multi-user multi-carrier cellular network that uses physical layer information to reduce inter-cell interference and upper layer information to stabilize the network. We have shown that our cross-layer approach stabilizes the network whenever the average arrival rates are within the achievable rate region. It also achieves a larger rate region than the baseline approach by protecting the data rate of users in neighboring cells.

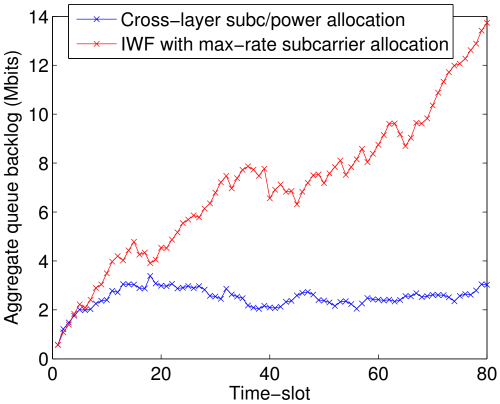

Fig. 3. Aggregate queue backlog of both cells comparing the proposed cross-layer approach and the baseline approach.

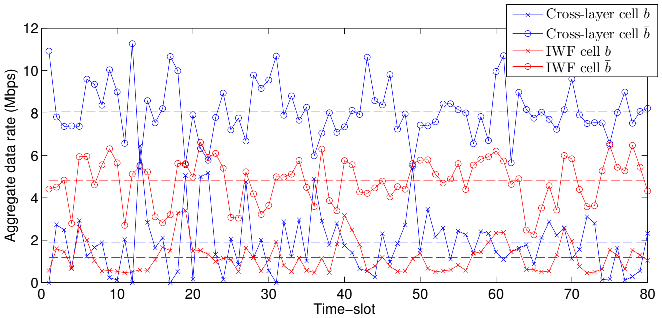

Fig. 4. Aggregate instantaneous and average data rates from the proposed cross-layer approach and IWF with max-rate subcarrier allocation. The dotted lines represent the average values.

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