Coordinated Resource Allocation for Downlink Transmissions: The Intra-Site Case

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Abstract—The latest generation of wireless networks use OFDMA (Orthogonal Frequency Division Multiple Access) transmission technology in the downlink (e.g., WiMAX [1] and LTE [2]). The downlink is divided into bandwidth units and UEs (User Equipments) are each allocated a subset of these. Since at most one UE is assigned to each of these units, downlink transmissions within a sector are orthogonal. However, the transmission is affected by intersector interference since UEs in adjacent sectors may also have been assigned to the resource. If the transmissions in neighbouring sectors are strong then the intersector interference may severely limit the SINR achieved by the UE. In this paper we consider a single site consisting of multiple sectors and consider the problem of maximizing the downlink capacity. We show that the sum rate, of a single resource unit, is maximized using a binary power allocation strategy. We then provide numerical results for a simple example to illustrate the gains that can be potentially achieved.

I. INTRODUCTION

The downlink bandwidth of the latest generation of wireless networks is divided into resource units each of which is allocated to at most one UE. For LTE, the downlink resource unit is termed a Resource Block (RB) and it consists of a fixed number of consecutive subcarriers while in WiMAX it is called a slot. In this paper we use the terminology for the LTE standard. UEs must be allocated RBs and, in addition, the amount of power allocated to these RBs must also be determined. These bandwidth and power decisions must be made so that each UE achieves its QoS goals while minimizing the negative effects caused by the resulting intersector interference. Therefore one must keep in mind intra-sector fairness (achieved through the scheduling of UEs within the sector), intra-site fairness (achieved through coordination of sector transmissions within the site) and inter-site fairness (achieved through power control and interference management).

In this paper we consider the case of a single site or eNB (Enhanced Node B) consisting of multiple sectors. Sectorization is used to achieve more efficient use of resources but downlink transmissions cause interference in adjacent sectors. Since the eNB receives information for all of its sectors then it can jointly allocate resources to achieve better performance. Such coordination can also be attempted across sites but that would require the exchange of eNB information over the backhaul and in practice will incur significant backhaul overheads as well as introduce delays in the exchanged information. Therefore we instead focus on joint optimization of resources for the intra-site case. Inter-site coordination is better handled with interference management schemes that operate over a larger time scale (see [3]). Hence we assume that interference management will dictate bounds on the amount of power the eNB can use for each RB in the frame. We first consider sum rate maximization over a single RB and assume no coordination of transmissions among the sectors within the site. Next we assume that a UE can be served from multiple sectors and hence achieve transmit diversity gains.

In [4] the case of two sites (or cells) with one sector per site was considered for the downlink. It was shown that the optimal power allocation for a single RB was binary which means that each UE is either served with full or zero power (i.e., it is not served). For the case of more than two cells the solution no longer has this binary power allocation solution. In [5] the two site case was also considered but for multiple RBs. In this case different resource allocation strategies are optimal for different scenarios. In this paper we consider a single site with multiple sectors.

In the next section we consider the case of one UE per sector and a single RB. We maximize the sum rate over all UEs in all sectors and show that the resulting solution is binary. Note that in this case we assume that the intersector interference is treated as noise. Next we assume that a UE can be served by more than one sector. Note that this can be done because the eNB has access to all transmission information. Finally we provide simulation results to illustrate the comparative gains that can be achieved.

II. SUM RATE MAXIMIZATION FOR A SINGLE RB

In this section we focus on the power allocation for a single RB. We assume \( N \) sectors and that a single UE is chosen for a potential packet transmission in each sector. Therefore the same index is used for the sector as well as for the UE allocated within that sector. Let \( g_{ij} \) denote the average channel gain from sector \( i \) to user \( j \). Therefore if sector \( i \) transmits with power \( p_i \) then the received signal strength of user \( i \) is \( p_i g_{ii} \) while the interference it incurs on user \( j \neq i \) is \( p_j g_{ij} \) (see Figure 1). Note that we will assume that each UE is interfered by exactly one sector (the closest neighbour). This assumption is reasonable because of the narrow beamwidth used by each sector. For convenience, we define the variable \( x_i = p_i g_{ii} \) which will be the decision variable. Given \( x_i \) we can then determine the transmission power of sector \( i \). We also
define the total interference experienced by user \( j \) by
\[
I_j = \sum_{i \neq j} p_i g_{ij}.
\]

The background noise experienced by UE \( j \) will be denoted by \( \sigma_j^2 \) and so the total interference plus noise at UE \( j \) is \( I_j + \sigma_j^2 \). The rate achieved in sector \( i \) can be determined from the received SINR of its transmitted packet. We constrain the decision variable by \( 0 \leq x_i \leq P_i g_{ii} \) where \( P_i \) denotes the maximum transmission power available for transmission over the RB.

A. Coordinated Resource Allocation

We first consider the case in which each sector transmits to its UE with some power and use the Shannon formula (with natural instead of base two logarithms) to determine transmission rates (normalized by the effective bandwidth for convenience). Therefore given the received SINR of UE \( i \), we determine the rate it achieves by
\[
r_i = \log \left( 1 + \frac{x_i}{I_i + \sigma_i^2} \right).
\]

Since our objective is to maximize the total rate, \( R \), over all UEs, then the optimization problem can be stated as
\[
\max_{\bar{x}} R(\bar{x}) = \sum_{i=1}^{N} \log \left( 1 + \frac{x_i}{I_i + \sigma_i^2} \right)
\]
subject to: \( 0 \leq x_i \leq P_i g_{ii}, \ i = 1, \ldots, N. \)

Suppose that we fix \( x_i \) for all \( i \neq k \) and consider the sum rate as a function of \( x_k \). Note that maximizing the sum of the logarithms is equivalent to maximizing the product of the arguments of the logarithms so we will instead maximize
\[
G(x_k) = \prod_{i=1}^{N} \left( 1 + \frac{x_i}{I_i + \sigma_i^2} \right).
\]

Next we use the fact that \( g_{kj} \) is zero for all \( j \) except for either \((k-1)\text{mod}(N)\) or \((k+1)\text{mod}(N)\). For convenience let us assume that \( k + 1 < N \) and that \( g_{kk+1} \) is the non-zero value.

Note that this means that \( I_i \) is independent of \( x_k \) for \( i \neq k + 1 \) and also we can write
\[
I_{k+1} = x_k g_{kk+1} + \sum_{j \neq (k+1)} p_j g_{jk+1}.
\]

We can therefore write
\[
G(x_k) = \\
\left( 1 + \frac{x_k}{I_k + \sigma_k^2} \right) \prod_{i \neq (k,k+1)} \left( 1 + \frac{x_i}{I_i + \sigma_i^2} \right).
\]

The first two terms depend on \( x_k \) but not the last term. We can rewrite this as
\[
G(x_k) = a \left( bx_k + \frac{c + dx_k}{e + fx_k} + 1 \right)
\]
where
\[
a = \prod_{i \neq (k,k+1)} \left( 1 + \frac{x_i}{I_i + \sigma_i^2} \right),
\]

\[
b = \frac{1}{I_k + \sigma_k^2},
\]

\[
c = x_{k+1} \left( I_k + \sigma_k^2 \right),
\]

\[
d = x_{k+1},
\]

\[
e = \left( I_k + \sigma_k^2 \right) \left( \sigma_k^2 + \sum_{j \neq (k,k+1)} p_j g_{jk+1} \right),
\]

\[
f = \left( I_k + \sigma_k^2 \right) \frac{g_{kk+1}}{g_{kk}}.
\]

Note that \( a, b, c, d, e \) and \( f \) are all non-negative. We can take the derivative of \( G(x_k) \) with respect to \( x_k \) to get
\[
\frac{dG}{dx_k} = ab + \frac{a(de - fc)}{(e + fx_k)^2},
\]
and the second derivative as
\[
\frac{d^2G}{dx_k^2} = -\frac{2af(de - fc)}{(e + fx_k)^3}.
\]

Now note that if \( de \geq fc \) then the first derivative is non-negative for the feasible range of \( x_k \) and hence \( G(x_k) \) is maximized when \( x_k \) reaches it maximum value at \( p_k = P_k \). If, on the other hand \( de < fc \) then the second derivative is positive and so \( G(x_k) \) is convex over the range of \( x_k \). Therefore it achieves a maximum at an extreme point. These points correspond to \( p_k = 0 \) and \( p_k = P_k \). We can repeat this argument for any sector to conclude that each sector is allowed to transmit with either full or zero power over the RB.

B. Coordinated Multi-Point Transmissions

In this section we assume that a sector may choose to serve it’s neighbour’s UE rather than its own UE in order to maximize the sum rate. This provides additional transmit diversity gains which can further improve the sum rate capacity. Consider sectors \( k - 1, k \) and \( k + 1 \). If they each serve their own UE then as we saw in the previous section,
binary power allocation is optimal. Next note that no more than two sectors can serve a UE because of the assumption that a UE experiences interference from exactly one other neighbouring sector. Therefore suppose that sectors $k$ and $k+1$ both serve UE $k$. To achieve reasonable transmit diversity gains we assume that the same power is used by each sector to serve the UE. Let us denote this power by $\hat{p}$. The received power can then be written as $p_k^r = \rho(\hat{p}g_{kk} + \hat{p}g_{k+1})$ where $\rho$ denotes the transmit diversity gain. This is the gain due to the fact that the transmissions are uncorrelated and hence the variance of their sum is smaller than the variance for the case of correlated transmissions. Therefore we can define an aggregate path gain $\hat{g} = \rho(g_{kk} + g_{k+1})$. Consider a new sector consisting of a combination of these two sectors containing only UE $k$. The received power for the UE is given by $\hat{p}\hat{g}$ and the interference to the UE in sector $k - 1$ is $\hat{p}\hat{g}g_{kk-1}$ while the interference to the UE in sector $k + 2$ is $\hat{p}\hat{g}g_{k+1+2}$. The resulting problem is exactly the same as the one described in the previous section and hence the optimal power allocation for serving UE $k$ is binary. In order to determine the optimal solution one must compute the sum rate for all possible combinations containing single transmissions and transmit pair transmissions.

Note that, instead of simply trying to achieve open loop transmit diversity gains one may also use MISO transmissions from both sectors to the single UE or even MIMO transmissions to serve both UEs from both sectors. However this requires a significant increase in the channel feedback required to perform these transmissions and in this paper we are assuming simple CSI feedback. With the use of MIMO the sum rate can be further increased because the UE SINR will increase while at the same time the interference to adjacent sectors will decrease. However, this beamforming causes changes in the interference pattern experienced by neighbouring sectors and hence one must simulate the entire network in order to evaluate the potential gains. With our assumptions, the beam pattern in each sector is fixed and hence as long as the transmission power is also fixed then the variance of the interference caused to neighbours is minimized.

III. Simulation Results

In this section we illustrate the performance gains achievable with using transmit diversity. For comparison purposes our baseline will be the case in which all sectors transmit with full power without any coordination or transmit diversity. One can use these comparisons to determine a suitable trade-off between performance and computational complexity.

For our performance comparison we use a simple simulation model of 3 sectors in a single site. We randomly drop one UE in each sector. We take into account path gains (with a path gain exponent of -3.5) and Shadow Fading (modelled as Log-normal with a Standard Deviation of 8dB). The antenna gain for each user is a slightly modified version of that used in [6]:

$$A(\theta) = -12 \left( \frac{\theta}{\theta_{3db}} \right)^2, \quad \theta_{3db} = 70^\circ.$$  

We assume a single transmit diversity gain factor $\rho$ for all potential sector pairs and will vary this from 0dB to 1.2dB. The same maximum power value is used for all sectors and this value is chosen so that the spectral efficiency of a UE at the edge of the sector is 0.1 bps/Hz.

Using multiple drops we determined the sum rate for the baseline case as well as for the case in which sectors can be paired for transmissions. We normalize the sum rate with that of the baseline case and plot this ratio for different values of $\rho$ in Figure 2. We find that, with $\rho = 1$ dB, transmit diversity is achieved for all drops. Hence with sufficiently good transmit diversity gains one can achieve significant performance gains by serving fewer UEs. Note that this is a single RB and hence sectors which do not serve its own UE will have the opportunity to do so in other RBs.

IV. Summary and Future Work

We considered the problem of allocating resources on the downlink of a OFDMA network consisting of a single site with multiple sectors. For the case of a single RB we showed that the optimal power allocation is binary (i.e., either zero or full power is used for transmissions in each sector). This also holds through if multiple sectors are used to serve a UE in order to achieve transmit diversity gains.

REFERENCES


Fig. 2. Dependence of Sum-Rate on $\rho$