Fairness of Link Adaptation Techniques in Broadband Wireless Access Networks

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Abstract—**Link adaptation techniques, such as power control and adaptive coding and modulation, aim at maximizing the resource utilization in wireless networks. However, fair resource allocation must be taken into consideration, particularly in fixed broadband wireless access networks. The low/no mobility of users in such networks leads to location-dependent resource utilization, which can cause a significant variation in the performance from a user to another. For instance, adaptive coding and modulation schemes increase the average throughput in the network; however, they also increase the variation of the throughput. This is because users with good link quality will *always* have high throughput, while users with bad link quality will *always* have low throughput. In this paper, the fairness and efficiency of various link adaptation techniques are analyzed. The analyzed algorithms are selected as a representative set of different link adaptation techniques with various fairness and efficiency characteristics.**

I. Introduction

Unlike wireline links, wireless links experience significant temporal and spatial variation in the link quality. In cellular networks, there are disadvantaged users who are close to the cell border or experiencing strong shadowing. On the other hand, there are advantaged users who are close enough to the basestations and might be experiencing no shadowing at all. The disadvantaged users usually suffer from a bad signal quality and/or high interference level, while the advantaged users usually have a good signal quality and a low interference level. In the first and second cellular generation systems, wireless networks are always designed based on the worst case scenario, so that all users including the disadvantaged ones are statistically guaranteed minimum quality of service in terms of the signal to interference ratio (*SIR*). However, this approach wastes part of the resources since the advantaged users experience much higher *SIR* than the minimum required value and these users do not make any use of it.

Power control (PC) has been proposed as a remedy to equalize the performance throughout the whole network by balancing the *SIR* of all users (see e.g. [1] & [2]). Alternatively, adaptive coding and modulation (ACM), exploits the variation in the signal quality (in terms of *SIR*) experienced by each user by allocating different coding and modulation levels to each user depending on the *SIR* or any related parameter (see e.g. [3] & [4]). Joint PC and ACM schemes have also been proposed for better resource utilization [5]. These schemes vary to a great extent in their fairness and efficiency. For instance, while PC tries to provide all users with almost the same signal quality and throughput, ACM provides users with largely varying signal quality and throughput. One the other hand, joint PC and ACM schemes can be considered as a compromise point between the two extremes (PC and ACM).

In this paper, we analyze the fairness and efficiency of various link adaptation techniques. The next section briefly presents the link adaptation techniques to be explored in this paper. The fairness and efficiency of the link adaptation techniques are analyzed in Section III. Section IV provides the results, and finally the conclusions and future work are given in Section V.

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II. Link Adaptation Techniques

The link adaptation algorithms studied in this paper are the following.

1. No PC – No ACM: The transmitted power, coding rate and modulation level are fixed. This case is considered as a reference system where link adaptation techniques are not utilized.

2. SIR-balancing PC (DCPC): The coding rate and modulation level are fixed while the transmitted power of user i at frame j $\{p(i,j)\}$ is dynamically updated using the distributed constraint PC (DCPC) algorithm [6] as follows

$$p(i,j) = \min\left\{ P_{max}, \frac{\delta\, p(i,j-1)\,\gamma}{SIR(i,j-1)} \right\} \quad , \tag{1}$$

where $SIR(i,j)$ is the *SIR* of user i at frame j, P_{max} is the maximum transmit power, γ is the target *SIR* and δ (>1) is a constant. The goal of such a scheme is to balance *SIR* such that all users can achieve the same *SIR* regardless of its location, channel conditions, or encountered interference level.

3. ACM: The transmitted power is fixed, while the coding rate and modulation level are adapted according to the achieved *SIR*. Before the beginning of each frame, the coding rate and modulation level are chosen based on the *SIR* achieved in the previous frame. Eleven combinations of coding rates and modulation levels are used as listed in Table I. Table I also includes the minimum required *SIR* of each combination of coding rate and modulation level at 10^{-6} bit error rate (BER) [7].

4. SIR-balanced PC followed by ACM (DCPC→ACM): The transmitted power is updated according to DCPC. Then, the coding rate and modulation level are chosen based on the achieved *SIR*. It should be noticed that although PC and ACM are both used here, this is not a joint PC and ACM since PC is used here to achieve the same *SIR* level for all users. Then ACM tries to allocate lower modulation level to user failed to achieve the targeted *SIR*.

5. Joint PC and ACM (SPC): The transmit power, coding rate and modulation level are updated using the selective PC (SPC) algorithm using the following formula [8]

$$p(i,j) = \max_{k} \left\{ \frac{\delta p(i,j-1)\gamma^k}{SIR\ \ (i,j-1)} \chi\left(\frac{\delta\, p(i,j-1)\,\gamma^k}{SIR\ \ (i,j-1)} < p_{max} \right) \right\} \quad , (2)$$

where γ^k is the target *SIR* corresponding to the coding rate and modulation level combination (k) and χ(a<b) is the indicator function which is equal to 1 if a<b and zero otherwise. This scheme tries to maximize the throughput by choosing the coding rate and modulation having the highest modulation efficiency based on the *SIR* level of the previous frame. Meanwhile, the transmitted power is adjusted to achieve the corresponding *SIR*.

6. Joint PC and ACM with link protection (SPC-ALP): The transmitted power, coding rate and modulation level are updated using SPC algorithm. However, new users as well as those seeking higher transmission rate can only increase their power incrementally. Meanwhile, some users who fail to achieve the minimum *SIR* are turned off temporarily as in the SPC with active link protection (SPC-ALP) algorithm [9].

7. Joint PC and ACM with link protection, cochannel interferer assistance and signal quality removal (SPC-ALP-ASQR): The transmitted power, coding rate and modulation level are updated using SPC-ALP with two additional features. The first feature is the cochannel users' assistance which means that if a user is can not achieve the minimum *SIR* (SIR_{min}), the cochannel interferers can assist by reducing their power level to avoid the temporary removal of that user. The second feature is the signal quality-based removal which means that the chosen users to be removed from the set of the unsupported users are the ones having the lowest *SIR* instead of the random selection proposed in [9]. This algorithm is called SPC-ALP with assistance and signal quality removal (SPC-ALP-ASQR) [10].

TABLE I
SIR OF DIFFERENT CODING- MODULATION LEVELS

Coding rate & modulation level index (k)	Coding rate & Modulation level combination	Spectral Efficiency (b/s/Hz)	*SIR* at 10^{-6} BER (γ^k) dB
1	1/2 & QPSK	1.00	4.65
2	2/3 & QPSK	1.33	6.49
3	3/4 & QPSK	1.50	7.45
4	7/8 & QPSK	1.75	9.05
5	1/2 & 16-QAM	2.00	10.93
6	2/3 & 16-QAM	2.66	12.71
7	3/4 & 16-QAM	3.00	14.02
8	7/8 & 16-QAM	3.50	15.74
9	2/3 & 64-QAM	4.00	18.50
10	3/4 & 64-QAM	4.50	19.88
11	7/8 & 64-QAM	5.25	21.94

8. Joint PC and ACM with link protection, cochannel interferer assistance, signal quality removal and channel reallocation (SPC-ALP-ASQRR): The transmitted power, coding rate and modulation level are updated using SPC-ALP-ASQR with another additional feature, channel reallocation, which means that the user(s) approaching the outage condition ($SIR<SIR_{min}$) can be switched to another channel if there is any available ones. The new channel has to have less intereference level than the current one. If there is not any available channels, the user will be switched to the assistance mode as explained above. This scheme is called SPC-ALP-ASQR with Reallocation (SPC-ALP-ASQRR) [10].

III. FAIRNESS AND EFFICIENCY ANALYSIS

As mentioned above, resource allocation schemes differ in their fairness. While some schemes try to balance the *SIR* and throughput of all users regardless of their channel conditions, other schemes exploit the variation in signal quality among users. The latter schemes might yield higher overall efficiency but leave some users with high amount of resources, whilst others get very little.

In fixed wireless networks, the resource allocation-dependence is a critical issue since a users in an unfavorable location will stay there forever; hence, such users will be always treated unfairly. On the other hand, in networks where there is high level of mobility, unfairness becomes less of an issue since a user with a bad link at some point in time will likely to have a good link at some other times (in a statistical sense). However, in mobile networks short-term fairness is not always attainable since some users might be stationary or having low mobility during their calls.

The mean throughput is always used to measure the efficiency of link adaptation techniques. Meanwhile, the throughput variance is a measure of the unfairness of the link adaptation scheme. Therefore, in order to quantify the fairness and efficiency of various link adaptation techniques, we will define the fairness coefficient (*FC*) as

$$FC = \frac{1}{1+V} \quad (3)$$

where V is the variance of the normalized throughput. This definition shows that *FC* is inversely proportional to the variance. And since the variance is a measure of the variation (unfairness) of the users, *FC* is a valid measure of the fairness. Also, it should be noted that *FC* ranges between 0 (no fairness) and 1 (100% fairness).

The efficiency coefficient (η) is defined as

$$\eta = \frac{M}{S_{max}} \quad (4)$$

where M is the mean of the normalized throughput and S_{max} is the maximum normalized throughput (modulation efficiency) of the coding rate and modulation level combinations listed in Table I. The normalized throughput is chosen instead of the actual throughput to make the results generic and comparable with other systems or schemes regardless of the channel bandwidth.

The fairness and the efficiency coefficients are determined for both the total normalized throughput and net normalized throughput, where the net throughput is defined as the useful throughput, i.e. the throughput after excluding the erroneous frames. Then, the mean of the total normalized throughput (M_{total}) can be expressed as

$$M_{total} = \frac{1}{N_u N_f} \sum_{i=1}^{N_u} \sum_{j=1}^{N_f} Thr(i,j) \quad (5)$$

where $Thr(i,j)$ is the normalized throughput (modulation efficiency) of the coding rate and modulation efficiency assigned to user i in frame j, N_f is the total number of frames transmitted during the simulation time, and N_u is the total number of users. The variance of the total throughput (V_{total}) is given by

$$V_{total} = \frac{1}{N_u} \sum_{i=1}^{N_u} \left(\frac{1}{N_f} \sum_{j=1}^{N_f} Thr(i,j) \right)^2 - M_{total}^2 \quad (6)$$

while the mean of the net normalized throughput (M_{net}) is defined as

$$M_{net} = \frac{1}{N_u N_f} \sum_{i=1}^{N_u} \sum_{j=1}^{N_f} Thr(i,j)\, \chi\{SIR(i,j) \geq \gamma\} \quad (7)$$

The variance of the net throughput (V_{net}) is given by

$$V_{net} = \frac{1}{N_u} \sum_{i=1}^{N_u} \left(\frac{1}{N_f} \sum_{j=1}^{N_f} Thr(i,j) \chi\{SIR(i,j) \geq \gamma\} \right)^2 - M_{net}^2 \quad (8)$$

IV. Results

Statistics of *SIR* and normalized throughput (total and net) are determined by computer simulation. A hexagonal cellular structure with 9 cells is considered. A wraparound grid is used to avoid the boundary effect. A TDMA system is assumed with 8 slots per frame. Directional antennas with a 60^o-beamwidth, main lobe gain of 20 dB, and side lobe gain of 0 dB are used at the basestation (BS). Similarly, Subscriber Stations (SSs) have directional antennas with a 60^o-beamwidth, main lobe gain of 15 dB, and side lobe gain of 0 dB. The channel model consists of an exponential path loss model with exponent (n) of 4, lognormal shadowing with a standard deviation (σ) of 8, and temporally-correlated flat Rayleigh fading [11]. A frequency reuse plan of 1/6 is employed such that the total spectrum is divided into 6 equal sub-bands allocated to the 6 sectors of each cell. The whole spectrum is reused every cell. This tight frequency reuse plan can be used since directional beams are employed at both BSs and SSs.

The pdf of *SIR* and normalized net throughput are plotted in Figs. 1 and 2 respectively. Both figures show the pdf of only 4 schemes for better clarity and due to the similarity of the general trend of the pdfs of some schemes. For instance, the pdf of the DCPC→ACM is much similar to that of DCPC alone. Likewise, the pdf of the four joint PC and ACM schemes (SPC, SPC-ALP, SPC-ALP-ASQR, and SPC-ALP-ASQRR) have similar shapes.

Schemes with fixed coding and modulation use the coding rate and modulation level combination (k) of 5, which corresponds to normalized total throughput of 2 b/s/Hz and targeted *SIR* (γ) of 10.93 as listed in Table I.

As shown in Fig. 1, the pdf of SIR of no PC – no ACM and ACM overlap since both schemes use fixed transmitted power. Both schemes have a very wide range of *SIR* values, which increases the *SIR* variance. Using DCPC for power control, the pdf of *SIR* has a narrower range and a peak around the targeted *SIR* (10.93 dB). This is expected since DCPC tries to balance *SIR*. However, it is evident that some users fail to achieve the target *SIR* value all the time, which causes the relatively high pdf values at *SIR* values less than 10.93. Joint PC and ACM has a medium range of *SIR*, which is smaller than that of the first two schemes but wider than that of DCPC. This is because joint PC and ACM schemes try to balance *SIR* but at multiple values (the 11 values listed in Table I). However, some coding rate and modulation level combinations are used more often than others. For instance, it is apparent that the 10^{th} coding rate and modulation level combination (with γ= 21.94) is used more often than the 1^{st} coding rate and modulation level combination (with γ=4.65) as reflected in the pdf of *SIR*.

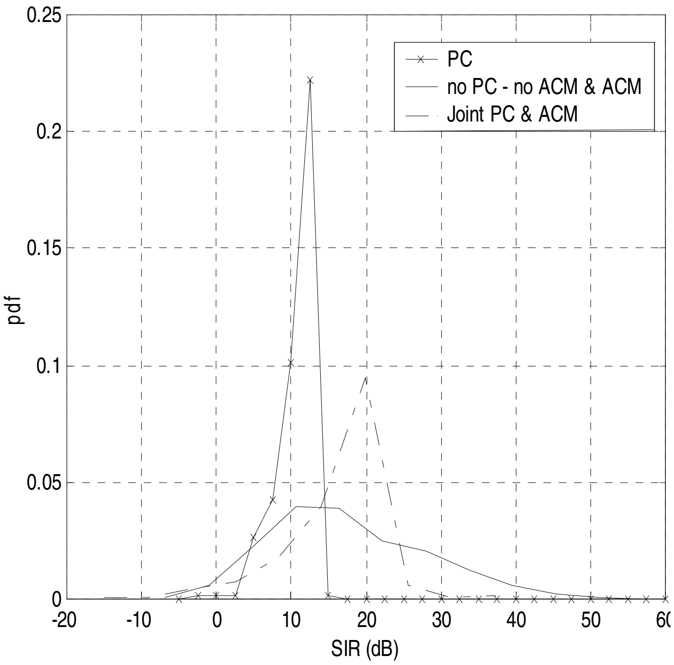

Fig. 1. pdf of the signal to interference ratio (*SIR*).

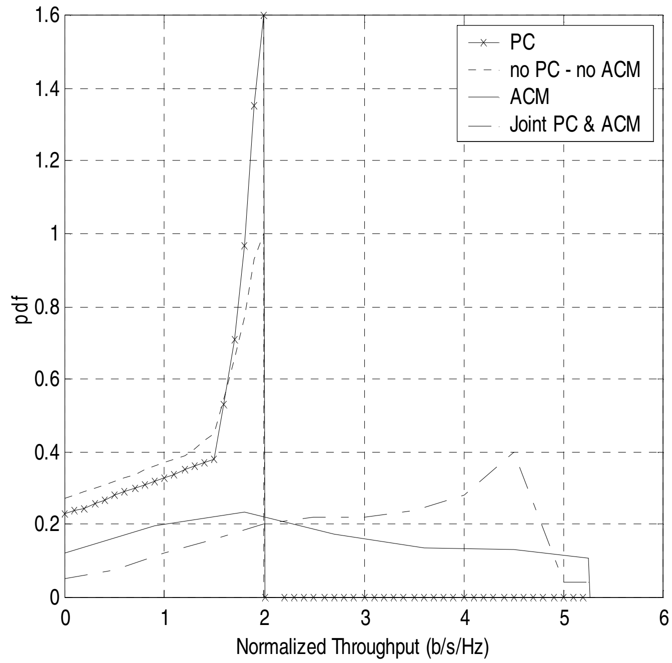

Fig. 2. pdf of the normalized net throughput per user.

Fig. 2 shows the pdf of the normalized net throughput per user. It is evident that schemes with fixed modulation (DCPC and no PC – no ACM) have a narrow range of throughput values, which leads to a smaller variance and hence a higher fairness coefficient. However, it is evident that DCPC has better efficiency and fairness than no PC-no ACM as depicted in Fig. 2 and Table II. With ACM, the normalized net throughput distribution is almost uniform. This is because ACM makes use of the wide range of the *SIR* values shown in Fig. 1 by adapting the coding rate and modulation level. Although this enhances the efficiency coefficient (η), it decreases the fairness coefficient (*FC*) as listed in Table II. Joint PC and ACM has a relatively wide range of throughput values with increasing trend up to 4.4 b/s/Hz.

As listed in Table II, fixed modulation schemes have ideal fairness for the total throughput (FC_{total}=1). However, they fail to achieve this for the net throughput due to transmission errors. Nevertheless, power control still has the highest FC_{net} (0.80), but with the second lowest efficiency coefficient of the normalized net throughput (η_{net}=0.26). If ACM follows DCPC, it can slightly enhance the efficiency coefficient of the normalized net throughput (η_{net}) to 0.29 without any significant reduction in the fairness coefficient (FC_{net}=0.79) compared to DCPC alone. However, ACM (without PC) enhances η_{net} considerably to 0.47 at the expense of having the lowest FC_{net} (0.32).

Joint PC and ACM schemes (particularly SPC and SPC-ALP-ASQR) have the highest η_{net} (0.53 and 0.51 respectively) with a low to medium FC_{net} (0.38 and 0.49 respectively). It is evident that the active link protection in SPC-ALP enhances the fairness, but at the expense of lowering the efficiency coefficient (η_{net}) from 0.53 to 0.41. The cochannel assistance and signal quality removal in SPC-ALP-ASQR enhances the efficiency coefficient of the normalized net throughput (η_{net}) from 0.41 to 0.46; however, this causes a reduction in the fairness coefficient of the normalized net throughput (FC_{net}) from 0.48 to 0.40. Channel reallocation is shown to be effective in enhancing both η_{net} and FC_{net} from 0.46 to 0.51 and from 0.4 to 0.49, respectively.

TABLE II
EFFICIENCY AND FAIRNESS COEFFICIENT OF TOTAL AND NET THROUGHPUT

Scheme	η_{total}	FC_{total}	η_{net}	FC_{net}
No PC – No ACM	0.38	**1**	0.22	0.67
DCPC	0.38	**1**	0.26	**0.80**
ACM	0.54	0.35	0.47	0.32
DCPC → ACM	0.35	0.94	0.29	**0.79**
SPC	**0.65**	0.39	**0.53**	0.38
SPC-ALP	0.52	0.43	0.41	0.48
SPC-ALP-ASQR	0.51	0.38	0.46	0.40
SPC-ALP-ASQRR	**0.60**	0.46	**0.51**	0.49

IV. CONCLUSIONS AND FUTURE WORK

Fairness and efficiency of different link adaptation schemes have been analyzed. It is shown that PC has good fairness but low efficiency, while ACM has high efficiency but low fairness. Joint PC and ACM schemes can achieve the highest efficiency with good fairness but still worse than the fairness of PC schemes. Hence, if fairness is the only concern, PC is the best option. Joint PC and ACM schemes can be the best option if efficiency is the main goal and fairness is a secondary one. ACM also can be a good option if high efficiency is required without the complexity of PC implementation where fairness is not considered or can be improved using some techniques.

It can also be concluded that channel reallocation can play an important role in enhancing the fairness of link adaptation techniques without causing any degradation in the efficiency. Channel reallocation can even enhance the efficiency as well. However, at high loading values channel reallocation can not enhance the performance because of the unavailability of free channels [10]. Further investigation of other fairness enhancement techniques such as multiple time slot allocation, variable maximum power constraints and throughput balancing is currently underway and to be published in a future paper.

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