Robust Proportional Fair Scheduling with Imperfect CSI and Fixed Outage Probability

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Abstract—Proportional fair (PF) scheduling is known to provide a balance between overall throughput maximization and fairness, by ensuring that users are served at one point in time, even if they experience poor channel conditions. In this regard, the PF scheduler accounts for the current channel state as well as for the throughput a user previously obtained. However, in slow fading scenarios with feedback delays the channel state information (CSI) known to the transmitter is outdated. Consequently, the transmission rates supported by the actual channel are only known imperfectly, which affects the scheduling as well as the rate adaptation, resulting in potential outages. While current schedulers typically ignore the CSI impairment, this work proposes a scheme which accounts for the variance of the CSI impairment and targets to achieve a fixed outage probability, referring to average delay constraints. Simulation results validate the advantages of the robust PF scheduling scheme when it is compared to non-robust solutions.

I. INTRODUCTION

The radio spectrum of cellular communications systems is limited and efficient resource allocation is required for increasing the average user throughput. Due to the varying nature of the mobile radio channel, multi-user diversity can be exploited by scheduling a particular radio resource to the user with the best channel [1], [2], also known as opportunistic scheduling. Although, this approach maximizes the overall throughput, users with poor channel conditions might never be scheduled.

Proportional fair (PF) scheduling maximizes the sum of the logarithmic user-throughputs [3], [4] and provides a compromise between performance maximization and user fairness [5]. PF scheduling has been analyzed for single-cell [6] and multi-cell networks [7], [8], while its extension to multi antenna systems has been discussed in [9], [10].

The before-mentioned contributions are based on the assumption of perfect knowledge of the instantaneous channel. However, in practical systems, channel state information (CSI) is only imperfectly available at the transmitter due to several sources of impairments, such as, channel estimation errors, feedback quantization as well as delays between channel observation and transmission [11], [12], relevant at slow fading channel conditions, as it is defined in [13]. Imperfect CSI has been studied in several works considering scheduling for throughput maximization [14]–[16]. However, to the best of the authors’ knowledge, so far no PF scheduling scheme is known which provides robustness against imperfect channel knowledge.

Due to the lack of exact CSI available at the transmitter, the rate achievable at the current channel state is not known precisely. This causes a non-optimal scheduling decision as well as imperfect rate assignment, which lead to potential outages [13]. For delay constraint applications, hybrid automatic repeat request (HARQ) [17], [18] is of little relevance and a fixed outage probability is of interest. For generalized fading channels, outage probability have been studied in [19] for receive combining techniques. Rate assignment for throughput maximization w.r.t. slow fading channels has been presented in [20], while fixed outage probability is considered in [21] for fast fading channels.

Contribution of this Work

In this paper, the authors present a rate adaptation method, which guarantees a fixed outage probability for slow fading channels with imperfect CSI at the transmitter. The results are incorporated into the PF scheduler in order to achieve robustness against impaired channel knowledge. With the presented scheduling scheme, a fixed outage probability and proportional fairness can be achieved at the same time. The algorithm additionally accounts for delayed CSI feedback. In this case the scheduler is not only uncertain about the CSI but also about the success of the latest transmissions. Consequently, the throughput currently achieved at a user is not precisely known. The results are analyzed w.r.t. the feedback delay, which is of special interest in cooperative cellular systems with backhaul latency [22], [23], relevant for cloud based 5G technologies [24].

The remainder of this paper is structured as follows. The system model is presented in Section II before outage probability results with imperfect CSI are given in Section III. Section IV examines the proposed PF scheduling scheme, while Section V shows simulation results followed by conclusions in Section VI.

Notation

Conjugate, transposition and conjugate transposition is denoted by $(\cdot)^*$, $(\cdot)^T$ and $(\cdot)^{\mathsf{H}}$, respectively. Expectation is $E\{\cdot\}$ and the probability of an event $A$ based on a given event $B$ is $P\{A|B\}$. Furthermore, $\mathbb{C}$ denotes the set of complex numbers and $\mathcal{N}(\mu, \sigma^2)$ refers to a complex normal distribution with mean $\mu$ and variance $\sigma^2$. 
II. SYSTEM MODEL

In this work a single-cell downlink system is assumed, where a base station (BS) serves \( K \) user equipments (UEs) on orthogonal radio resources, such as, time-frequency elements in orthogonal frequency division multiple access (OFDMA) systems. The instantaneous radio channel between the BS and UE \( k \) is denoted with \( h_k \sim \mathcal{N}_C(0, \lambda_k) \), where \( \lambda_k \) is the mean channel gain of UE \( k \). A collection of contiguous resource elements experiencing a constant channel state is referred to as transmission block. In this work, a transmission block corresponds to a time slot and is indexed with \( n \). The channel of UE \( k \) at time slot \( n \) is denoted as \( h_k[n] \). It is assumed that at each time slot the BS transmits to a single user only, using the full available bandwidth.

Due to user mobility the channel varies in time, where the correlation between two channel coefficients, delayed by \( \Delta \) time slots is

\[
\mathbb{E}(h_k[n]h_k^*[n + \Delta]) / \lambda_k = J_0\left(\frac{\Delta}{T_c}\right),
\]

where \( T_c \) and \( J_0 \) are the normalized coherence time and the zero-th order Bessel function of the first kind, respectively. The constant \( q = J_0^{-1}(0.5) \) determines, that at a delay of \( T_c \), the correlation between channel and its delayed version is 0.5. In this work slow fading is assumed, where the channels of subsequent time slots show strong correlations.

With perfect knowledge of the instantaneous channel state \( h_k[n] \) at the BS, the maximum achievable transmission rate for UE \( k \) is

\[
C_k[n] = \log_2 \left(1 + \frac{\rho[n]\lambda_k}{\sigma_n^2}\right),
\]

where \( \rho[n] \) is the power of the transmitted signals at time slot \( n \), while the receiver noise power \( \sigma_n^2 = 1 \) is set to one. The signal-to-noise-ratio (SNR) experienced at UE \( k \) is given by \( \gamma_k[n] = \rho[n]\lambda_k/\sigma_n^2 = \rho\lambda_k \). In this case (2) refers to the channel capacity. Considering a long-term power constraint, the capacity is achieved by adapting the transmit power \( \rho \) at each time slot to the respective channel state [13]. However, this work assumes an instantaneous power constraint with a fixed power allocation of \( \rho[n] = \rho, \forall n \). Note, that (2) is based on the assumption of perfect rate assignment, i.e., the maximum rate supported by the instantaneous channel need to be allocated for transmission.

A. Imperfect CSI

In practical systems, CSI need to be available at the BS in order to perform rate assignment and multi-user scheduling. In frequency division duplex (FDD) systems, the downlink channel cannot be obtained from corresponding uplink measurements but is observed at the UE side and fed back to the BS via an uplink control channel with limited capacity. Consequently, the CSI available at the BS is impaired by channel estimation errors, feedback quantization and potential delays between channel observation and data transmission, where the latter effect can be mitigated by employing channel prediction. A detailed description of the underlying feedback model used in this work, is presented in [25].

With imperfect CSI, the BS is uncertain about the actual channel \( h_k[n] \), \( \forall k \). Based on the uncertainty and the used feedback model, the channel of each UE \( k \) is a complex Gaussian random variable. In case of minimum mean square error (MSE) estimation, the mean value of \( h_k[n] \) refers to the instantaneously available channel estimate \( \hat{h}_k[n] \), while its variance \( \epsilon_k \) reflects the respective channel uncertainty [26]. Note, that \( \epsilon_k/\lambda_k \) refers to the normalized channel uncertainty and ranges between zero and one. Consequently, the actual channel

\[
h_k[n] \sim \mathcal{N}_C(\hat{h}_k[n], \epsilon_k)
\]

can equivalently be written as the sum of the channel estimate and a zero mean Gaussian random error \( \epsilon_k[n] \sim \mathcal{N}_C(0, \epsilon_k) \), as

\[
h_k[n] = \hat{h}_k[n] + \epsilon_k[n].
\]

Since the mean gain of the actual channel is \( \lambda_k \) and the variance of the error is \( \epsilon_k \), the mean gain of the channel estimate is reduced according to the error variance

\[
\mathbb{E}(\hat{h}_k[n]^2) = \lambda_k(1 - \epsilon_k/\lambda_k).
\]

B. Rate Adaptation and Throughput

As mentioned before, for achieving the rate in (2), the same rate needs to be assigned for transmission. However, with imperfect channel knowledge, the achievable rate is not known at the transmitter. Consequently, the allocated transmission rate either exceeds channel capacity or it does not. While in the latter case, the channel capacity is potentially not fully exploited, the first case suffers from outage, i.e., the package received at the UE cannot be decoded correctly with infinitesimal error probability [13].

In this regard, function \( S_k[n] \) indicates the success of the transmission to user \( k \) in time slot \( n \), i.e., \( S_k[n] \) is equal to one if the transmission is successful and zero otherwise. With the rate assigned for transmission \( \hat{R}_k[n] \), the actually experienced rate at UE \( k \) in time slot \( n \) is \( R_k[n] = S_k[n]\hat{R}_k[n] \). The probability of outage (\( S_k[n] = 0 \)) is given as

\[
p_{\text{out}, k}[n] = P\left\{ \log_2 \left(1 + \rho|h_k[n]|^2\right) < \hat{R}_k[n] \right\}.
\]

For the fast fading case, the CSI at the transmitter is assumed to be uncorrelated with the actual channel. Based on (5), a time slot independent rate assignment scheme can be derived for guaranteeing a fixed outage probability [13], [21].

The throughput UE \( k \) obtained until time slot \( N \) by taking non-successful transmissions into account results in

\[
T_k[N] = \frac{1}{N} \sum_{n=1}^{N} R_k[n] = \frac{1}{N} \sum_{n=1}^{N} S_k[n]\hat{R}_k[n].
\]

While throughput maximization is discussed in [20], this work focuses rate adaptation with fixed outage probability, as it is of interest for delay constrained applications. Furthermore, the more challenging case of slow fading channels is considered.
III. ROBUST RATE ADAPTATION WITH IMPERFECT CSI

In the following, the $k$th UE index is as well as the time slot index $n$ is omitted for improving readability. Furthermore, the amplitude of the actual channel and those of the CSI is denoted as $g = |h|$ and $\hat{g} = |\hat{h}|$, respectively.

For the slow fading case considered in this work, it is assumed, that the channel information available at the BS is correlated with the actual channel and can be exploited in order to adapt the transmission rate to the current channel fading state.

Utilizing the results of [13], [19], the probability of outage conditioned on the available side information $\hat{g}$ is given as

$$p_{\text{out}} = \mathbb{P}\left\{ \log_2 \left( 1 + pg^2 \right) < \hat{R} \mid \hat{g} \right\}$$

$$= \mathbb{P}\left\{ g < \sqrt{(2R-1)/\rho} \mid \hat{g} \right\}$$

$$= F_{g|\hat{g}} \left( \sqrt{(2R-1)/\rho} \right),$$

where $F_{g|\hat{g}}(x)$ denotes the cumulative distribution function (CDF) of $g$ conditioned on $\hat{g}$ at the point $x$.

The amplitude of a complex Gaussian non-zero mean random variable follows a Rician distribution [13]. Consequently, the probability density function (pdf) of $g$ conditioned on $\hat{g}$ can be written as

$$f_{g|\hat{g}}(g) = \frac{2g}{\epsilon} \exp \left( -\frac{g^2 + \hat{g}^2}{\epsilon} \right) J_0 \left( \frac{2g\hat{g}}{\epsilon} \right),$$

where $J_0(x) = \sum_{l=0}^{\infty} (x/2^{2l}/l!\Gamma(l+1))$ refers to the modified Bessel function of the first kind and order zero, while $\Gamma(x)$ is the gamma function.

The CDF in (7) is obtained by integration over (8) from zero up to $b = \sqrt{(2R-1)/\rho}$, as

$$F_{g|\hat{g}}(b) = \int_0^b f_{g|\hat{g}}(g) dg.$$ (9)

With the results of [27], the integral in (9) can be solved to

$$F_{g|\hat{g}}(b) = 1 - Q_1 \left( \sqrt{\frac{2b^2}{\epsilon}, \sqrt{\frac{2b^2}{\epsilon}} \right) \sum_{m=0}^{\infty} \left( \frac{\hat{g}}{\epsilon} \right)^m J_m \left( \frac{2\hat{g}}{\epsilon} \right).$$ (10)

where $Q_1$ is the Marcum Q-function and $J_m(x) = \sum_{l=0}^{\infty} \frac{1}{l!(l+m+1)} \left( \frac{x}{2} \right)^{2l+m}$ is the modified Bessel function of the first kind and order $m$.

Consequently, the resulting outage probability with the given estimated amplitude of the channel $\hat{g}$ results in

$$p_{\text{out}} = 1 - \exp \left( -\frac{g^2 + \hat{g}^2}{\epsilon} \right) \cdot \sum_{m=0}^{\infty} \left( \frac{\hat{g}}{\sqrt{2} \hat{g}} \right)^m J_m \left( \frac{2\sqrt{2} \hat{g}^2}{\epsilon} \right).$$ (11)

However, solving (11) for $\hat{R}$ is not known and numerical solutions are applied to determine the transmission rate assigned for obtaining the outage probability $p_{\text{out}}$. 

Fig. 1. Rate assigned for transmission as a function of the amplitude of the available channel estimate.

Fig. 2. Target outage probability as a function of the transmission rate which need to be assigned on average in order to achieve the target.

Fig. 1 shows the rate allocated as a function of the estimate’s amplitude. With increasing target outage probability, more aggressive rates are allocated. The black line refers to non-robust rate allocation (RA), where the available CSI is assumed to be perfect. With decreasing error variance $\epsilon$, the robust RA converges to the non-robust RA. Fig. 2 illustrates the target outage probability as a function of the transmission rate assigned on average. For guaranteeing an outage probability of 0.1, about 2 bits per channel use (bpcu) can be allocated on average if no CSI is available at the transmitter. In this case, the respective rate need to be assigned at each time slot. For CSI with a normalized uncertainty of $-10$ dB, more than 3 bpcu and for $-20$ dB almost 4 bpcu can be allocated on average. Note, that in these cases the rate assigned at the individual time slots depends on the actual CSI version available.
IV. ROBUST PROPORTIONAL FAIR SCHEDULING WITH IMPERFECT CSI

In this section, the proportional fair (PF) scheduler is derived for the case of imperfect channel knowledge. While the previous section presented rate adaptation independent of user and time slot, in this section the respective indexes are utilized again.

Assuming UE $k$ is served in time slot $n$, the rate expected to be achieved refers to

$$\hat{R}_k[n] = E\{R_k[n]\} = (1 - p_{out,k})\bar{R}[n],$$

(12)

the product of the probability of a successful transmission and the respective transmission rate. Since the experienced user rate is not precisely known to the transmitter, it refers to a random variable with mean value $\bar{R}_k[n]$. Consequently, it can be written as

$$R_k[n] = \hat{R}_k[n] + \Psi_k[n],$$

(13)

the sum of the expected rate and a bias $\Psi_k[n]$. The experienced rate is either the rate $\hat{R}_k[n]$ assigned for transmission or zero.

Hence, the bias term results in

$$\Psi_k[n] = \left\{\begin{array}{ll}
\hat{R}_k[n] - \bar{R}_k[n] & \text{if } \hat{R}_k[n] < R_k[n] \\
-\bar{R}_k[n] & \text{otherwise}
\end{array}\right.$$

(14)

By definition, the expectation of $\Psi_k[n]$ is zero, since

$$E\{\Psi_k[n]\} = (1 - p_{out,k})(\hat{R}_k[n] - \bar{R}_k[n]) - p_{out,k}\bar{R}_k[n]$$

$$= (1 - p_{out,k})\bar{R}_k[n] - \hat{R}_k[n] = 0.$$  

(15)

With the given rate model the derivation of the PF scheduler is extended to the case of imperfect CSI. In this regard, immediate and delayed feedback is distinguished. The first case corresponds to precise knowledge of the user throughput experienced up to the latest time slot, while in the latter case, the success of the previous $\Delta$ transmissions is not known to the scheduler.

A. Immediate Feedback

With the indicator function $I_k[n]$, which is one if UE $k$ is scheduled at time slot $n$ and zero otherwise, the throughput $U_k$ experiences up to time slot $N$ is given as

$$T_k[N] = \frac{1}{N}\sum_{n=1}^{N} I_k[n]R_k[n]$$

$$= \frac{1}{N}\left(\sum_{n=1}^{N-1} I_k[n]R_k[n] + I_k[N]R_k[N]\right)$$

(16)

$$= \frac{N-1}{N}T_k[N-1] + \frac{1}{N}I_k[N]R_k[N].$$

Note, that the throughput refers to the overall number of bits successfully decoded up to time slot $N$, normalized to the overall time slots $N$. The expected throughput results in

$$E\{T_k[N]\} = \frac{N - 1}{N}T_k[N-1] + \frac{1}{N}I_k[N]\bar{R}_k[N],$$

(17)

where the second summand results from the zero mean random bias term, as given in (15). Note, that for immediate feedback, the throughput of the previous time slot $T_k[N-1]$ is assumed to be precisely known to the scheduler. The throughput values of all $K$ UEs given in (16) are collected in vector

$$\mathbf{T}[N] = [T_1[N], \ldots, T_K[N]]^T.$$  

(18)

As defined in [7], the PF scheduler aims to maximize the utility function

$$u(\mathbf{T}[N]) = \sum_{k=1}^{K} \log (T_k[N])$$

(19)

for an infinite number of time slots, expressed as

$$\max_{\mathbf{T}} \lim_{N \to \infty} \sum_{k=1}^{K} \log (T_k[N]).$$

(20)

The gradient of (19) results in

$$\nabla u(\mathbf{T}[N]) = [\frac{\partial u(\mathbf{T}[N])}{\partial T_1[N]}, \ldots, \frac{\partial u(\mathbf{T}[N])}{\partial T_K[N]}]^T$$

$$= [T_1[N]^{-1}, \ldots, T_K[N]^{-1}]^T.$$  

(21)

Since the scheduler acts on time slot basis, the utility increment is of interest, which can be expressed by

$$u(\mathbf{T}[N]) - u(\mathbf{T}[N-1]) \simeq$$

$$\nabla u(\mathbf{T}[N-1])^T (\mathbf{T}[N] - \mathbf{T}[N-1])$$

$$= \sum_{k=1}^{K} \frac{T_k[N]-T_k[N-1]}{T_k[N-1]}$$

(22)

$$= \sum_{k=1}^{K} \frac{I_k[N]R_k[N]-T_k[N-1]}{N T_k[N-1]}$$

$$= \frac{\sum_{k=1}^{K} I_k[N][\bar{R}_k[N] + \Psi_k[N]]}{N T_k[N-1]} - \frac{K}{N}.$$  

Consequently, maximizing the utility increment (22) results in scheduling the UE with the largest value for

$$\nu_k[n] = \frac{I_k[N][\bar{R}_k[N] + \Psi_k[N]]}{T_k[N-1]}.$$  

(23)

Since $\Psi_k[N]$ is unknown at the scheduler, maximizing the expected utility increment $E\{\mu_k[n]\}$ leads to scheduling the UE with the largest value for

$$\hat{\nu}_k[n] = E\{\nu_k[n]\} = \frac{I_k[N]\bar{R}_k[N]}{T_k[N-1]},$$

(24)

where (24) also maximizes the utility function $u(E\{\mathbf{T}[N]\})$.

B. Delayed Feedback

Now, the previously derived robust PF scheduler is extended to the more realistic case of delayed feedback, where the success of each transmission at the previous $\Delta$ time slots is not known to the scheduler. Consequently, the throughput $U_k$ achieved up to time slot $N$ is a discrete random variable. Since UE $k$ has been scheduled $\eta = \sum_{n=N-\Delta}^{N-1} I_k[n]$ times within the period of interest. Since the success of those transmissions is unknown to the scheduler, there are $2^\eta$ constellation options.
Hence, the throughput equation (16) can be rewritten to

\[
T_k[N] = \frac{1}{N} \left( \sum_{i=1}^{N-\Delta} I_k[i] R_k[i] + \sum_{j=\Delta}^{N-1} I_k[j] R_k[j] + I_k[N] R_k[N] \right) \\
= \frac{N-\Delta}{N} T_k[N-\Delta-1] + \frac{1}{N} \sum_{j=\Delta}^{N-1} I_k[j] R_k[j] + \frac{1}{N} I_k[N] R_k[N].
\]  

(25)

While the first summand of the sum \( c_0 = (N - \Delta - 1)/N \cdot T_k[N - \Delta - 1] \) is known to the scheduler, the second and third one can be split up according to (13).

The utility increment as stated in (22) is given as

\[
E\{u(T[N]) - u(T[N-1])\} = \frac{N-1}{N} \sum_{k=1}^{K} \frac{I_k[N] R_k[N]}{c_0 N + D} - \frac{K}{N},
\]

(26)

where \( D = \sum_{j=\Delta}^{N-1} I_k[j] R_k[j] \) is a discrete random variable with \( M \) events, each of which denoted as \( d_m, \forall m \). Consequently, maximizing the expected utility increment leads to scheduling the user with the largest value

\[
\hat{v}_k[n] = E\left\{ \frac{I_k[N] R_k[N]}{c_0 N + D} \right\} \\
= E\left\{ \frac{I_k[N] R_k[N]}{c_0 N + D} + \frac{I_k[N] \Psi_k[N]}{c_0 N + D} \right\} \\
= E\left\{ \frac{I_k[N] R_k[N]}{c_0 N + D} \right\}.
\]

(27)

The third line in (27) is obtained, since the expectation w.r.t. the discrete random variable can be split up into a finite sum. With \( E\{\Psi_k[n]\} = 0 \), the right summand in the second line of (27) is equal to zero. The expectation in the third line can be obtained by summing over the \( M \) discrete events, weighted by the probability of occurrence, to

\[
\hat{v}_k[n] = I_k[N] R_k[N] \frac{M}{c_0 N + \sum_{m=1}^{M} P\{D = d_m\}}.
\]

(28)

As for immediate feedback, (28) maximizes the utility function \( u(E(T[N])) \) for the delayed feedback case.

V. SIMULATION RESULTS

For illustrating the effect of the proposed scheduling schemes, Monte-Carlo simulations have been performed, considering a simple scenario, where a single BS serves two users on orthogonal resources (one at a time slot). Both users are assumed to have the same long-term channel statistics, i.e., the same path loss and fading statistics. The simulations are averaged over 10000 channel realizations, where each realization consists of the channel states of \( N = 20 \) time slots.

PF scheduling is performed with perfect CSI (P-CSI) and imperfect CSI (I-CSI), while for the latter case non-robust scheduling as well as the proposed robust scheduling is performed. Non-robust scheduling refers to the case where the scheduler assumes the available CSI to be precise, although its actually imperfect. For comparison, also round robin scheduling is simulated, where the users are selected alternately, without taking the instantaneous channel state into account.

The throughput summed over both users as a function of the target outage probability is illustrated in Fig. 3. The black solid line refers to PF scheduling with perfect CSI. Performing the same algorithm with CSI impaired by an error of \( \epsilon = -10 \text{ dB} \), result in a performance drop of almost 50 % (green dashed line). Employing the proposed robust algorithm (blue solid line), the target outage probability (abscissa) is achieved on average, which is of interest for delay sensitive applications. The resulting outage probability for non-robust scheduling is at about 0.4, which does not match the given requirements for the most of the region in Fig. 3. Furthermore, throughput gains compared to the non robust scheme can be obtained for target outage probabilities between 0.002 and 0.4, while the throughput maximizing outage probability is at 0.1. Note, that the respective throughput can even be improved by a scheduler which instantaneously adapts the outage probability according to the channel state. Round robin scheduling (gray dotted line) performs slightly worse than the non-robust PF scheduler. Note, that both schemes are utilizing non-robust rate adaptation. In practice the rate assigned for transmission might be reduced by a preselected back-off factor, in order to reduce the outage probability. However, the choice of the respective value is static and instantaneous rate optimization is not possible with this approach.

The throughput as a function of the feedback delay (normalized to the duration of a transmission block) is illustrated in Fig. 4, where the feedback model presented in [25] is used. Here, the PF algorithm presented in Section IV-B is used, employing robustness against CSI impairments as well as against delayed decoding acknowledgments from the receiver. Since the CSI accuracy increases with the delay, the
throughput performance decreases for both, the robust and the non-robust PF scheduler. However, the reasons are for the performance loss are different. For the non-robust algorithm, the rate adaptation is not affected but the outage probability increases. In contrast, the robust algorithm achieves its outage targets by decreasing the assigned rate.

VI. CONCLUSIONS

In this work, a robust rate adaptation scheme together with a robust proportional fair (PF) scheduling algorithm have been presented, where both take into account that the available CSI is impaired. The algorithms are aiming to achieve a fixed outage probability, as it is of interest for delay critical applications. The robust PF algorithm has been derived for immediate as well as for delayed feedback, where for the latter case, the throughput experienced by the users during the latest transmissions is not known to the base station. Simulation results illustrated the advantage of the proposed schemes compared to non-robust PF scheduling.

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