Delay Bounds for Resource Allocation in Wideband Wireless Systems

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Abstract— **In this paper, the problem of resource allocation in multiuser single-antenna wideband OFDM(A) systems is considered from a cross-layer point of view. The main motivation is to show advantages of such systems with respect to narrowband systems. Despite the maximum normalized average throughput is not increased with respect to that in a narrowband system, a more efficient use of resources is possible by considering frequency as an additional resource to be allocated. It is shown that when the bandwidth is considerably larger than the coherence bandwidth of the channel and the channel is varying slowly with respect to the scheduling period, average delay can significally be improved. In that case, the average delay is only proportional to the scheduling period and not to the channel coherence time (as it is the case in narrowband systems). Furthermore, different reasource allocation policies are analyzed to show average delay improvements when buffer occupancy information is used.**

I. Introduction

This paper tackles with the problem of resource allocation in multiuser single-antenna systems transmitting over *wideband frequency-selective channels* from a cross-layer perspective. Any OFDM system such as the IEEE 802.16 standard where an Orthogonal Frequency Division Multiple Access (OFDMA) technique is proposed or the UTRAN HSDPA (high-speed data packet-access) 3GPP proposal using an OFDM(A) physical layer instead of WCDMA for the downlink channel [1] can be considered as an example of the systems that we consider in this paper. In this context, algorithms to allocate the different frequency sub-bands and appropriate power levels on each sub-band to users will be considered. Whereas such kind of algorithms have been largely studied and proposed in the literature from a PHY layer perspective, the study of resource allocation in wideband frequency-selective channels in terms of parameters such as delay or queue stability, is, to the best of our knowledge, a completely new approach.

We are interested in resource allocation strategies which exploit multiuser diversity by means of accurate channel state information at the transmitter. The gains offered by multiuser diversity techniques with respect to constant power allocation over all resources can be seen as either a significant increase in spectral efficiency as the user population grows (which amounts essentially to a factor of two for low signal-to-noise ratios) or equivalently in transmit power savings [2]. Basically, multiuser diversity scheduling techniques base their performance on exploiting the users' channel randomization induced by the channel variability and, at each time instant, allocating the channel to the user with best channel conditions. Unfortunately, in scenarios with low user mobility, channel might vary very slowly (slow fading channel) compared to the delay constraints so that transmission cannot wait until their channel becomes the best channel condition.

However, the key advantage of wideband OFDM(A) systems with respect to narrowband systems is the possibility of performing multiuser scheduling both in time and frequency. Although the attainable average throughput (normalized with respect to the bandwidth) is not increased by the wideband resources [3], [4], in this paper we show that the additional dimensions increase randomness in the system and hence, potentially allow for placing bandwidth or delay constraints.

Considerations of average packet delay when performing scheduling in time varying channels were presented in [6] and references therein. In [6] the authors analyze the stability and delay of power and rate allocation in a multibeam satellite downlink which transmits data to K different ground locations over K time varying channels (beams). They present a resource allocation algorithm that, according to the queue lengths and the channel state allocates power and rate in order to achieve system stability. The work of Neely and Modiano was considered by Yeh and Cohen [7] in order to analyze the multiple access and broadcast wireless channels. In that work, the authors presented a resource allocation policy that allocates power and rate considering the queue length as a reward. Hence, they argue that solutions to the ergodic capacity optimization problem presented in [4] are yet applicable considering that the queue length establishes the priority order in the allocation of powers and rates. Both works, [6] and [7], assume a block fading channel that varies independently from time-slot to time-slot. A more general case is considered in [8], where the channel might vary slowly with respect to the scheduling time (or time-slot). Delay bounds in [6], [7] and [8] show that average delay in narrow band systems is proportional to the channel coherence time. In [9], Boche and Wiczanowski considered the Multiple Input Multiple Output (MIMO) multiple access channel ending up with the same resource allocation policy and similar delay bounds as in [7], [6] or [8]. In [10], Kobyashi et al. considered a SDMA/TDMA system with delayed feedback where the variability of the channel was increased by using opportunistic beamforming techniques. The latter was also considered in [11] where the limitations in terms of delay when performing

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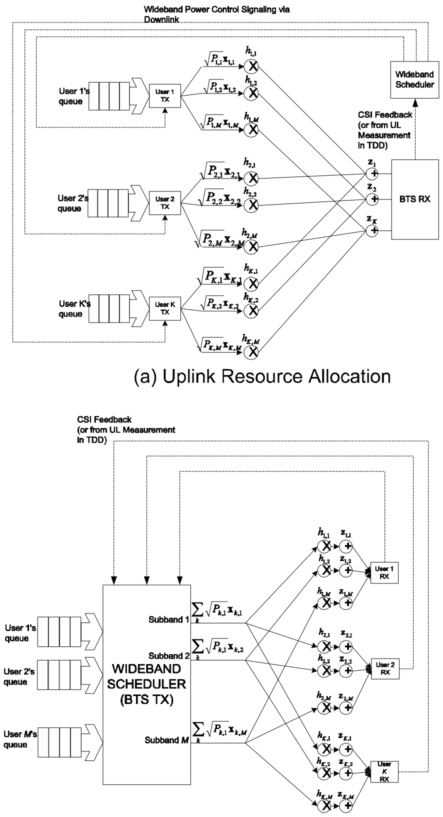

(b) Downlink Resource Allocation

Fig. 1. System Scenarios

opportunistic beamforming for single user channels is assessed and the use of multiple channels in order to consider multiuser communications is introduced. In this work, which is a continuation of that presented in [16], we follow the same machinery as in [8] to assess potential average delay improvements of resource allocation in wideband frequency selective channels and to show that, ideally, 0 seconds average packet delay could be achieved even in very slow fading channels.

II. The Channel and Signal Models

The systems under consideration are shown in figure 1 and are the downlink and uplink channels in cellular or Wireless LAN network topologies. Channel access is assumed to be time-slotted, with slot duration T sec. The scheduler will allocate power and rate to the user streams every slot. Note that in a real system there will necessarily be a signaling delay of a few slots for uplink scheduling which is neglected here for simplicity. Interference between slots is neglected by using appropriate guard-times of duration greater than the typical delay-spread of the propagation channels and significantly shorter than T so that information rate loss is negligible.

A. The Channel Model

In order to model wideband channels we assume M parallel discrete-time channels. This is a typical way of discretizing a waveform channel [12]. Moreover, in the context of digitally sampled OFDM systems, the use of a cyclic prefix allows the channel to be considered as a memoryless system in the discrete Fourier transform-domain (DFT) and the parallel channels just represent frequency samples over the system bandwidth. Each channel is characterized by a complex channel gain $h_{k,m}(t)$, $k=1,2,\cdots,K$, $m=1,2,\cdots,M$, which corresponds to the amplitude and phase of the m^{th} channel for user k at time-slot t. Our channel model is a block channel fading model where the channel gains $h_{k,m}(t)$ are assumed to remain constant during one time slot but can vary from time-slot to time-slot. Particularly, in the spirit of OFDM-based systems, each channel gain $h_{k,m}(t)$ could be modeled as a frequency sample of a discrete multipath channel having Γ significant uncorrelated paths with delays: $\tau_1,\tau_2,...,\tau_\Gamma$, that is $h_k(t)=\sum_{i=0}^{\Gamma-1}\alpha_i\delta(t-\tau_i)$, where the path gains α_i are zero mean Gaussian random variables with variance σ_i^2. The samples of the frequency response are given by $h_{k,m}(t)=H_k(f_m)=\sum_{i=0}^{\Gamma-1}\alpha_i e^{-j2\pi\tau_i f_m}$, where $H_k(f)=\int_{-\infty}^{\infty}h_k(t)e^{-j2\pi ft}df$ and have covariance

$$E\left\{h_{k,m}(t)h_{k,m'}^*(t)\right\}=\sum_{i=0}^{\Gamma-1}E\left\{|\alpha_i|^2\right\}e^{-j2\pi\tau_i\left(f_m-f_m'\right)}$$

where f_m is the absolute frequency corresponding to sub-band m, and the channel coherence bandwidth is given by $1/\tau_\Gamma$. Furthermore, let us define T_c as the channel coherence time (in time-slots), i.e., the number of time-slots at which, for any given initial time-slot t_0, the channel gains $h_{k,m}(t_0)$ and $h_{k,m}(t_0+T_c)$ are independent.

Consider that $h_{k,m}(t)$ are stationary and identically distributed random variables and let the vector $\mathbf{h}_m(t)=[h_{1,m}(t),...,h_{K,m}(t)]$ represent the vector process of the users' channel gains at frequency sub-band m and time-slot t. Then, define the empirical cumulative distribution function as,

$$F_{t_0,m_0}^{N,M}(\mathbf{x})=\frac{1}{M}\frac{1}{N}\sum_{m=m_0}^{m_0+M-1}\sum_{t=t_0}^{t_0+N-1}\prod_{k=1}^{K}1\{h_{k,m}(t)\leq x_k\}$$

Assume that the empirical cumulative distribution function converges with probability 1 to a deterministic cumulative distribution $F_{\mathbf{h}}(\mathbf{x})$ when $MN\to\infty$. Furthermore, we assume that the channel procees is such that for any value $\delta>0$, there exist integer values of M and N such that for all initial values t_0 and m_0,

$$\int\left|E_{t_0,m_0}\left\{dF_{t_0,m_0}^{N,M}(\mathbf{x})\right\}-dF_{\mathbf{h}}(\mathbf{x})\right|\leq\delta \quad (1)$$

Clearly, in the case that $h_{k,m}(t)$ are i.i.d. random variables, $M=1$ and $N=1$ even for $\delta=0$. In general, many tuples (M,N) can be a solution for a given value δ. This means that one can make the empirical cumulative function converge to its deterministic value by either increasing M, N or both. Particularly, note that the convergence with respect to M and

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N, strongly depends on the channel coherence bandwidth $(1/\tau_\Gamma)$ and the channel coherence time (T_c), respectively.

B. The Signal Model

For the case of an uplink channel (multiple-access channel) the signal at the receiver is given by (note that time-slot index t is omitted for commodity)

$$y_m = \sum_{k=1}^{K} \sqrt{P_{k,m}} h_{k,m} x_{k,m} + z_m \qquad m = 1, 2, \cdots, M \tag{2}$$

where $x_{k,m}$ is the kth user transmitted symbol through frequency sub-band m, $P_{k,m}$ is the instantaneous transmit energy used by user k on channel m and z_m is additive white complex circularly-symmetric Gaussian random sequence with variance σ_z^2 and mean zero. It is assumed that the receiver (basestation) can adjust the $P_{k,m}$ based on channel state information (CSI) measurements, and moreover that these are signalled (via the downlink) and received without error at the user terminals. The basestation estimates the CSI for each user from received pilots which are known signals transmitted *over the entire bandwidth over which power allocation is performed.* Note that for slowly-varying channels this is reasonably simple to accomplish and consumes little signaling bandwidth since the allocation remains invariant across several slots. The considered instantaneous power constraints are

$$\sum_{m=1}^{M} P_{k,m} \leq P_k \qquad P_{k,m} \leq \frac{P_k}{M} \tag{3}$$

For the downlink (broadcast channel), the signal at receiver k is given by

$$y_{k,m} = h_{k,m} \sum_{k'=1}^{K} \sqrt{P_{k',m}} x_{k',m} + z_{k,m} \qquad m = 1, 2, \cdots, M, \; k = 1, 2 \cdots, K \tag{4}$$

where $z_{k,m}$ is additive white complex circularly-symmetric Gaussian random sequence with variance σ_z^2 and mean zero. The considered instantaneous power constraint is

$$\sum_{k=1}^{K} P_{k,m} \leq \frac{P}{M} \tag{5}$$

where the expectation is over the random channels. Note that this is the general non-orthogonal broadcast channel.

III. Resource Allocation and Rate Convergence

A. Resource Allocation

A complete characterization of the ergodic capacity region of wideband fading multiple-access channels was found in [4]. The ergodic sum rate was found in [3]. Define $\mathbf{P}_m = \{P_{1,m}(t), ..., P_{K,m}(t)\}$, $\mathbf{P} = \{\mathbf{P}_1^t(t), ..., \mathbf{P}_M^t(t)\}$ and $\mathbf{H} = \{\mathbf{h}_1^t(t), ..., \mathbf{h}_M^t(t)\}$. Furthermore, for a given rate vector $\mathbf{R}_m = \{E\{r_{1,m}(t)\}, ..., E\{r_{K,m}(t)\}\}$, consider the notation $R_m(S) = \sum_{k \in S} E\{r_{k,m}(t)\}$.

Then, the ergodic capacity region is a solution the resource allocation problem that corresponds on optimally allocating powers $P_{k,m}(t)$ and rates $r_{k,m}(t)$ such that,

$$\max_{\mathbf{R},\mathbf{P}} \boldsymbol{\mu} \cdot \mathbf{R} - \boldsymbol{\lambda} \cdot \mathbf{P} \;\; s.t. \;\; R \in C(\mathbf{H}, \mathbf{P}) \tag{6}$$

where,

$$C(\mathbf{H}, \mathbf{P}) = \bigcup_{\substack{\sum_m P_{k,m} \leq P_k \\ k=1,\ldots,K}} \left\{ \mathbf{R} = \sum_m \mathbf{R}_m : \mathbf{R}_m \in \mathcal{C}(\mathbf{h}_m, \mathbf{P}_m) \right\} \tag{7}$$

and

$$\begin{aligned} C(\mathbf{h}_m, \mathbf{P}_m) = &\{\mathbf{R}_m : R_m(S) \\ &\leq E\left\{ \frac{W}{M} \log\left(1 + \frac{\sum_{k \in S} |h_{k,m}(t)|^2 P_{k,m}(t)}{\sigma_z^2}\right) \right\}; \\ &\forall S \subseteq \{1, 2, ..., K\}\} \end{aligned} \tag{8}$$

$\boldsymbol{\mu}$ is a vector of rate rewards (priorities for each user), $\boldsymbol{\lambda}$ is a vector of Lagrange multipliers reflecting the total power constraints for each user and W is the system bandwidth. The optimal information rate $r_{k,m}(t)$ on each sub-band and $P_{m,k}(t)$ are readily found by generalizing the results of [4] to the discrete sub-band case. A particular user will be assigned power on a given sub-band if it yields the maximum increase in the objective function, and in general more than one user will be allocated power on a particular sub-band. As a result, in the general case, a multiuser receiver (e.g. using interference cancellation) is required to detect each user's signal because of the non-orthogonal channel access.

A more practical approach that yelds to single user receiver solutions is to consider discrete power levels such that $P_{m,k}(t) \in \{0, P'\}$. Then, the multiple access channel and the broadcast channel optimization problems are equivalent. And, by the convexity of the logarithmic function, the solution to the optimization problem (6) is,

$$P_{k,m}(t) = \begin{cases} P' \text{ if } k = \arg\max_k \left\{ \mu_k \frac{W}{M} \log(1 + \frac{|h_{k,m}(t)|^2 P'}{\sigma^2}) \right\} \\ 0 \text{ otherwise} \end{cases} \tag{9}$$

where P' is $\frac{P_k}{M}$ for the multiple access channel and $\frac{P}{M}$ for the broadcast channel.

B. Rate Convergence

Since the power $P_{k,m}(t)$ allocated to each user at each frequency sub-band migth change from time-slot to time slot according to $\mathbf{h}_m(t)$, the allocated rate $r_{k,m}(t)$ might also change from time-slot to time-slot and from sub-band to sub-band. Since, each channel state is mapped to a user rate, given the channel process described in section II-A, define the average rate as,

$$\overline{r}_{k,m} = E\left\{r_{k,m}(t)\right\} = \int E\left\{r_{k,m}(t)|\mathbf{h}_m(t)\right\} dF_{\mathbf{h}}(\mathbf{x}) \quad (10)$$

Then, following lemma 4 in [8], it can be easily shown that the rate process is a rate convergent process such that, for any $\delta > 0$ there exist integer values of M and N that for all t_0 and m_0,

$$\left| E\left\{ \frac{1}{M}\frac{1}{N} \sum_{m=m_0}^{m_0+M-1} \sum_{t=t_0}^{t_0+N-1} r_{k,m}(t) \right\} - \overline{r}_{k,m} \right| \leq R_{\max}\delta \quad (11)$$

where $R_{\max}$ is the maximum value of $r_{k,m}(t)$. In the next section we will make use of the Lyapunov drift analysis in the same way as in [8] in order to show that rate convergent processes as defined above can reduce average packet delay in wideband systems compared to that in narrow band systems.

IV. System Considerations and Stability region

Information bits for user k are retrieved from a queue which buffers packets of L bits each. Then, given that $N(t)$ packets arrive at buffer k during slot t, consider the general arrival process $A_k(t) = \sum_{i=1}^{N(t)} L(i)$ that represents the number of bits that arrive in slot t. Assume that $A_k(t)$ are i.i.d. from slot to slot with an average rate of λ_k bits/sec, $k = 1, 2, \cdots, K$ and bounded second moment arrivals $E\left\{A_k^2(t)\right\} < \infty$. During time-slot t, bits for user k are sent at $\sum_m r_{k,m}(t)$ bits/sec. The number of backlogged bits of each user at the beginning of each time-slot is represented by $S_k(t)$ and evolves according to

$$S_k(t+1) = \left[S_k(t) - \sum_m r_{k,m}(t) \right]^+ + A_k(t)$$

where $[x]^+$ indicates $\max(0, x)$. A system is said to be stable if $\lim_{S\to\infty} g_k(S) = 0$ for all $k = 1, ..., K$ where $g_k(S) = \limsup_{t\to\infty} \frac{1}{t} \sum_{\tau=1}^{t} \mathbf{1}\left\{S_k(t) > S\right\}$ is the buffer overflow function. Then, following [8], the stability region Λ of our system is given by the set of *all* arrival rate vectors $\boldsymbol{\lambda} = [\lambda_1, ..., \lambda_k, ..., \lambda_K]$ such that,

$$\lambda_k \leq \sum_m \overline{r}_{k,m}$$

or equivalently,

$$\rho_k = \frac{\lambda_k}{M} \leq \overline{r}_{k,m} \quad (12)$$

Notice that restricting the resource allocation policy to take decisions according to the channel state only, does not restrict the stability region [8]. Then, for any given vector $\boldsymbol{\rho}$ that lies strictly in the interior of the stability region Λ we can find a value $\epsilon > 0$ such that $\boldsymbol{\rho}+\epsilon\mathbf{1}$ also lies in the capacity region and hence,

$$\rho_k + \epsilon \leq \overline{r}_{k,m}$$

Then, given that the rate process is rate convergent, there must exist values for M and N such that

$$E\left\{ \frac{1}{M}\frac{1}{N} \sum_{m=m_0}^{m_0+M-1} \sum_{t=t_0}^{t_0+N-1} r_{k,m}(t) \right\} - \rho_k \geqslant \epsilon - R_{\max}\delta \quad (13)$$

such that $0 < R_{\max}\delta < \epsilon$ where $R_{\max}\delta$ is defined by (11).

Assuming that vectors $\mathbf{S}(t) = [S_1(t), .., S_K(t)]$ represent a Discrete Time Markov Chain (DTMC), we can establish the following lemma,

Lemma 1: The optimal resource allocation policy guarantees that the average delay is upper bounded by,

$$\sum_k \rho_k \overline{D_k} \leq \frac{TKN\left(R^2 + \frac{A_{\max}^2}{M^2}\right)}{2(\epsilon - R_{\max}\delta)} \quad (14)$$

where $A_{\max}^2 = \max_k E\left\{A_k^2(t)\right\}$ and $R^2 = E\left\{ \left(\frac{1}{M}\frac{1}{N}\sum_{m=m_0}^{m_0+M-1}\sum_{t=t_0}^{t_0+N-1} r_{k,m}(t)\right)^2 \right\}$.

And for symmetric users (users with equal average input rates)

$$\overline{D} \leq \frac{TN\left(R^2 + \frac{A_{\max}^2}{M^2}\right)}{2(\epsilon - R_{\max}\delta)\rho} \quad (15)$$

Proof: A sketch of the proof is given in appendix.

Furthermore, according to (11) a value for M can be found such that $N = 1$ and then, assuming symmetric users,

$$\overline{D} \leq \frac{T\left(R^2 + \frac{A_{\max}^2}{M^2}\right)}{2(\epsilon - R_{\max}\delta)\rho} \quad (16)$$

Notice that according to expression (11), the value of δ can be reduced by increasing M without the need of increasing N. Hence, setting $N = 1$ and thanks to the additional dimension introduced by the M frequency sub-bands, the delay bound is only proportional to the duration of a time-slot T (which is also the scheduling time) and does not depend on the channel coherence time as it was the case in narrowband channels [6], [8]. Ideally, one could set $\delta = 0$, i.e., $M = \infty$, and then minimize the delay. Furthermore, if buffers could be filled and emptied infinitely fast ($T = 0$), average packet delay could be lowered to zero. However, from an implementation point of view, note that, increasing M means increasing the number of operations the scheduler must perform in T sec which in some cases might be not affordable.

V. Results

Two different resource allocation policies have been compared. One is the Proportional Fair Scheduling (PFS) policy. The PFS is such that, at each sub-band, resources are allocated according to,

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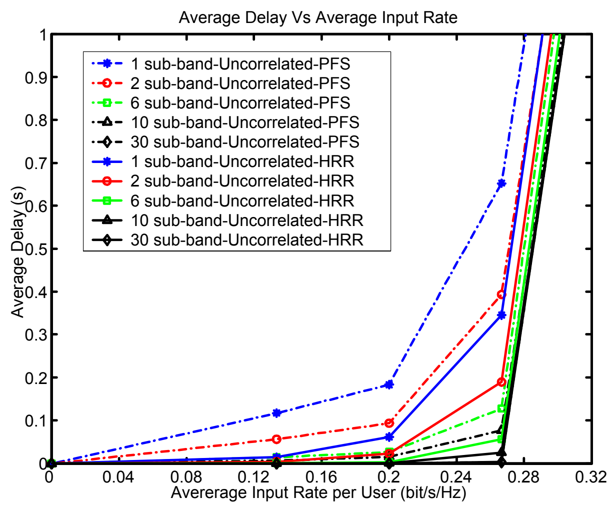

Fig. 2. Average delay Vs average input rate in frequency uncorrelated channels.

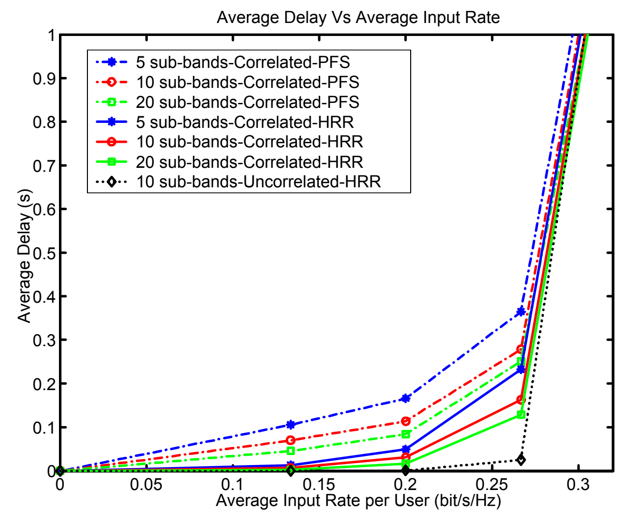

Fig. 3. Average delay Vs average input rate in frequency correlated channels.

$$P_{k,m}^{PFS}(t) = \\ = \begin{cases} P' \text{ if } k = \arg\max_k W \log_2(1 + \frac{|h_{k,m}(t)|^2 P'}{\sigma^2}) \\ 0 \text{ otherwise} \end{cases}$$

where W is the frequency sub-band bandwidth and P' is either equal to $\frac{P}{M}$ in the downlink case or equal to $\frac{P_k}{M}$ in the uplink case. In any case, we have considered P' such that the average received signal to noise ratio $(\frac{P'}{\sigma^2})$ is $0dB$.

The second scheduling policy is called the Highest Rewarded Rate (HRR) resource allocation policy. The HRR allocates resources to users according to

$$P_{k,m}^{HRR}(t) = \\ = \begin{cases} P' \text{ if } k = \arg\max_k \left\{ S_k(t) W \log_2(1 + \frac{|h_{k,m}(t)|^2 P'}{\sigma^2}) \right\} \\ 0 \text{ otherwise} \end{cases}$$

for $m = 1, .., M$. Notice that the HRR policy is equivalent to the optimal resource allocation (6) but the user priorities are given by the instantaneous user buffer state S_k. In [8], it is demonstrated that the HRR scheduling policy also stabilizes the system whenever the average input rates are inside the stability region defined by (12).

We have considered 6 users in the system with packet arrivals following a Poisson process with average input rate of ρ_k $(bit/s/Hz)$. According to the system specifications provided in [17], slot duration $T = 300\mu s$ and channel coherence time $T_c = 64T = 19.2ms$ are considered. The frequency subband bandwidth W has been set to $0.5MHz$ and for the correlated channel results, it has been considered an exponentially decaying multipath intensity profile with 21 uncorrelated paths with equally spaced delays and a delay spread of $1\mu s$. With such parameters, every time-slot, the channel realizations $h_{k,m}(t)$ have been generated as explained in section II-A.

Figure 2 shows average delay as a function of ρ_k in the uncorrelated channel case. Results for PFS and HRR policies are presented. Curves representing the 1 frequency sub-band case show the limitations in terms of delay of narrowband systems in the presence of slow fading channels. When the number of frequency sub-bands is increased average delay is significantly improved because channel randomness is increased and hence, the rate convergent process converges faster to its average value. For instance, we observe that for the case of 30 frequency sub-bands, average delay is approximately zero (for both resource allocation policies) as long as the average input rate is inside the stability region. According to the behavior observed in figure 2, one would expect that in the ideal case of $T = 0s$ and $\delta = 0$ (given by expression 11), i.e., $M = \infty$, the resultant average delay curve would be a step function of $0s$ delay for all the rates inside the stability region and infinite delay otherwise. We also observe that the HRR policy always performs better that the PFS policy. This is because taking into account cross-layer information such as the buffer state information allows for a more efficient allocation of channel resources.

In figure 3 it is shown the effect of frequency channel correlation for both resource allocation policies, PFS and HRR. Clearly, it is seen that frequency channel correlation has a strong effect on the average delay and that, more frequency sub-bands are necessary in order to obtain similar results as for the uncorrelated channel case. Furthermore, we observe that channel correlation affects more as the average input rate increases.

VI. Conclusions

This paper presents average delay bounds for resource allocation in wideband wireless systems. Particularly, we have shown that if there exists a resource allocation policy that

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leads to a rate convergent process, average delay can be made arbitrary small by increasing the number of frequency sub-bands M and reducing the scheduling time T. The number of frequency sub-bands necessary to achieve a desired average delay bound is strongly related to the channel coherence bandwidth. Such effect has been studied in simulations.

Although the PFS policy stabilizes the system in the symmetric user case, in general, resource allocation policies that allocate resources using CSI only, lead to system unstability unless additional information on average arrival rates and channel statistics is also used. Hence, such resource allocation policies might be impractical sometimes. In this paper, it is also shown how resource allocation policies that use cross-layer information, as buffer occupancy information, not only would simplify scheduling in the asymmetric user case but also make a more efficient use of resources showing lower average delays.

VII. Appendix

Proof of lemma 1. Consider the MN- step dynamics of the unfinished work as follows:

$$S_k(t_0+N) \leq$$
$$\left[S_k(t_0) - T\sum_{t=t_0}^{t_0+N-1}\sum_{m=1}^{M} r_{k,m}(t)\right]^+ + \sum_{t=t_0}^{t_0+N-1} A_k(t)$$

To simplify notation consider,
$S_k(t_0) = S_k$ and $S_k(t_0+N) = S_k(N)$,
$R_k = \frac{1}{N}\frac{1}{M}\sum_{t=t_0}^{t_0+N-1}\sum_{m=1}^{M} r_{k,m}(t)$,
$A_k = \frac{1}{N}\sum_{\tau=t_0}^{t_0+N-1} A_k(t)$.
Opperating, we obtain,

$$\begin{aligned} S_k^2(N) &\leq S_k^2 - 2S_kT(NMR_k - N\frac{A_k}{T}) + \\ &+ (NMR_k)^2T^2 + (NA_k)^2 \end{aligned}$$

Now using the definition of Lyapunov function $L(\mathbf{S}) = \sum_k S_k^2$. We find,

$$\begin{aligned} E\{L(\mathbf{S}(N)) - L(\mathbf{S})\} &\leq T^2N^2M^2K\left(R^2 + \frac{A_{\max}^2}{M^2}\right) - \\ &-2TNM\sum_k S_k\left(E\{R_k|\mathbf{S}\} - \rho_k\right) \end{aligned}$$

Then, since the allocation policy that maximizes rate does not depend on $\mathbf{S}$, and given (13),

$$E\{R_k|\mathbf{S}\} - \rho_k = E\{R_k\} - \rho_k \leq \epsilon - R_{\max}\delta$$

and

$$\begin{aligned} E\{L(\mathbf{S}(N)) - L(\mathbf{S})\} &\leq T^2N^2M^2K\left(R^2 + \frac{A_{\max}^2}{M^2}\right) - \\ &-2TNM\sum_k S_k(\epsilon - R_{\max}\delta) \end{aligned}$$

and applying lemma 2 given by [8],

$$\sum_k \overline{S_k} \leq \frac{TKNM\left(R^2 + \frac{A_{\max}^2}{M^2}\right)}{2(\epsilon - R_{\max}\delta)}$$

Following Little's theorem,

$$\sum_k (M\rho_k)\overline{D_k} \leq \frac{TKNM\left(R^2 + \frac{A_{\max}^2}{M^2}\right)}{2(\epsilon - R_{\max}\delta)}$$

and,

$$\sum_k \rho_k\overline{D_k} \leq \frac{TKN\left(R^2 + \frac{A_{\max}^2}{M^2}\right)}{2(\epsilon - R_{\max}\delta)}$$

□

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