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Abstract: Scheduling in a Downlink channel based on partial Channel State Information at the Transmitter (CSIT) is carried out through an opportunistic technique. Within a more practical perspective, this paper first presents a transmission strategy where a minimum rate per user is required, which in a wireless fading scenario, can only be guaranteed under a certain system outage constraint. This minimum rate is demanded within a given time interval to satisfy maximum delay restrictions for the user application. Closed form expressions for maximum scheduling delay and maximum jitter are obtained, standing as possible Quality of Service (QoS) indicators for the system behaviour. The derived expressions are then tested via simulations in several transmission scenarios.

Key–Words: Opportunistic transmission, HSDPA-HDR, Maximum delay, QoS.

1 Introduction

The Opportunistic transmission schemes are attractive due to their high performance, and at the same time, low complexity design, as recently been commercialized through the UMTS-HSDPA and Qualcomm's-HDR standards. But while maximal sum rate has typically been considered as the objective of opportunistic schemes [1], an alternative approach that focuses on the QoS of the served users is required for a system implementation [2]. A potential measure of the system QoS is through the minimum rate per user, so that each served user is guaranteed a minimum Signal-to-Noise-Ratio (SNR), allowing it to properly decode its intended data with a predefined Packet Error Rate (PER).

Regarding the minimum requirement per user, previous studies [3] have shown that the user satisfaction is insignificantly increased by a performance higher than the user demands, while on the other hand, if the provided resources fail to guarantee its requirements, the satisfaction drastically decreases. Thus, a good scheduling scheme is achieved through satisfying the minimum requirements for the available users in the system.

Furthermore, the wireless operators realize that some users can provide deficient channel conditions for communication, and delivering service to such users can be very expensive in term of system resources, driving down the whole system performance; so that if these users are dropped, the operator can offer better service to all the remaining users in the system. Based on this practical point of view, operators are more interested in probability of outage measures [4] rather than absolute QoS fulfillment, making all the commercial systems to fix a target probability of outage in the users QoS.

Concerned with the QoS achievement in HSDPA-HDR, the opportunistic technology is shown to boost the cellular system performance by increasing the total system rate and efficiency, as it exploits the channel variations of the several users in the cell. But to obtain its highest rates, it can only operate QoS delay-tolerant applications that do not require for hard delay deadlines to correctly operate, as the maximum delay in packets delivery is not tightly controlled by the wireless operator. An alternative approach to control the QoS delay, is to provide some fairness in the resource allocation process, but this comes at expenses of lower rates [5]. But almost all the applications intended for HSDPA-HDR and future 4G systems require for high data rates, while they are QoS delay constrained through a wide range of applications as video-conferencing, video-streaming and online gaming among others, therefore, these applications can not obtain all the benefits from the opportunistic technology and its superior efficiency.

This paper with the use of the outage concept, therefore matching with the practical application of opportunistic schemes to cellular HSDPA-HDR systems, formalizes the service distribution statistics, and is able to use them in obtaining the closed form solutions for the maximum scheduling delay and minimum rate per user. This provides a tool to optimize the system performance, as a tight QoS control over the awarded rate and the maximum scheduling delay is obtained, therefore adapting the HSDPA-HDR behaviour to meet the system requirement for all the applications.

Very few works deal with QoS in opportunistic schemes [2], and no one (to the best of our knowledge) has presented the analytical expressions of the QoS maximum delay, related to opportunistic systems in outage scenarios. Moreover, with the delay expressions at hand, the system maximum delay jitter can be also characterized, which is actually a hard restriction for the system performance. Several applications need a fixed rate for the packets entering the applications decoder, where all commercial systems make use of the playout buffers [6, Chp.6] to deal with the random channels nature.

The remainder of this paper is organized as follows: while section II deals with the system model, in section III a review of the opportunistic procedure is presented. Section IV presents the system QoS performance under outage specifications and derives the corresponding maximum scheduling delay and jitter equations. The numerical results and simulations are in section V, to end with the paper conclusions in section VI.

2 System Model

We focus on the Downlink channel where N receivers, each one of them equipped with a single receiving antenna, are being served by a transmitter at the Base Station (BS) also provided with a single transmitting antenna. A channel $h(t)$ is considered between each of the users and the BS where a quasi static block fading model is assumed, which keeps constant through the coherence time, and independently changes between consecutive time intervals with independent and identically distributed (i.i.d.) complex Gaussian entries $\sim \mathcal{N}(0,1)$. Therefore each user is assumed to keep fixed during each fading block, and allowed to move from block to block. Let $s_i(t)$ denotes the uncorrelated data symbol to the i^{th} user with $E\{|s_i|^2\} = 1$, then the received signal $y_i(t)$ is given by

$$y_i(t) = h_i(t)\, s_i(t) + z_i(t) \qquad (1)$$

where $z_i(t)$ is an additive i.i.d. complex noise component with zero mean and $E\{|z_i|^2\} = \sigma^2$. A total transmission power of $P_t = 1$ is assumed, and for ease of notation, time index is dropped whenever possible.

3 Opportunistic Transmission

One of the main transmission techniques in multiuser scenarios is the opportunistic technique [1][7], where during the acquisition step, a known training sequence is transmitted for all the users in the system, and each one of the users calculates the received SNR, and feeds it back to the BS. The BS scheduler chooses the user with the largest SNR value for transmission to benefit from its current channel situation, and therefore improving the global system performance.

This opportunistic strategy is proved to be optimal [1][7] as it obtains the maximum rate point. But it has been shown to be unfair as some user providing a low channel SNR can starve until it is serviced, so that several proposals in literature [5][7] presented some kind of fair resource allocation schemes through modified scheduling techniques, which have been actually implemented for the commercial HSDPA-HDR standards. Unfortunately, providing fairness comes at the expenses of lower system rate [5], where fairness stands as the used QoS indicator.

This paper considers an alternative service policy as it operates the HSDPA-HDR system under the highest possible rate, but it provides the closed-form expressions for the maximum delay and minimum rate, so that a precise QoS control is presented with all the involved variables that can be optimized. Notice that these concepts stand as QoS realistic constraints for both delay constrained and tolerant applications, providing the commercial operator with a wider view than the fairness concept, as the QoS is stated in terms of per user exact requirements.

4 System QoS Performance

Once the rate benefits of the opportunistic schemes have been stated in several works in the literature [5][7], it turns to be the time to analyze their QoS performance. QoS can be characterized by several metrics or indicators based on the design objectives, so that QoS can be in terms of rate, reflecting the minimum required rate per user, or in terms of delay, showing the maximum delay that a user can tolerate. This paper considers both concepts of QoS, where the transmission scheme guarantees a minimum rate per user, which is presented by minimum SNR restriction (snr^{th}) per each user in the system, and delivered to it within a given maximum time delay.

As this work looks for realistic objectives within the HSDPA-HDR systems, it further drives the opportunistic schemes towards a practical point of view, through adapting an alternative service policy, where a predefined probability of outage ξ_{out} in the service rate is tolerated [4], as done in cellular GSM and UMTS systems, and proposed for HSDPA-HDR and 4G systems.

The paper defines two concepts for outage [8], where the first one is related to the access scheme answering to the question: when the i^{th} user will be provided service? Subsection (4.1) characterizes the user access process to the system service and obtains the expression for its access probability. If a user does not access the channel within its maximum allowed delay, it is declared as being in delay outage ξ_{access}. The second outage source comes through the awarded rate to answer the question: Once the i^{th} user is selected for transmission, would it receive a data rate below its requirements? Subsection (4.2) uses the rate distribution for the selected user, and obtains the minimum guaranteed rate under an outage ξ_{rate}, where the two kinds of outages are designed to meet the global system outage ξ_{out}.

4.1 Delay Outage

This section identifies the exact maximum time slot when the user will be served by the BS.

Definition: Given $\overline{P}_{access}$ as the probability of success on each trial, the probability that K independent trials are required to select an element i from a group of N i.i.d. elements, is defined as the Geometric Distribution [9], having a cumulative distribution function (cdf)

$$V(K) = 1 - (1 - \overline{P}_{access})^K \tag{2}$$

which states that with a probability V, the i^{th} element is selected in the first K trials.

This definition matches the users access in an opportunistic scheme, where each one of the independent users tries to access the channel, with $\overline{P}_{access} = \frac{1}{N}$. Therefore, the maximum number of time slots until the i^{th} user is selected with a probability of outage $\xi_{access} = 1 - V$, is given by

$$K = \frac{\log_2(1-V)}{\log_2(1-\overline{P}_{access})} = \frac{\log_2(\xi_{access})}{\log_2(1-1/N)} \tag{3}$$

where the effect of higher number of active users N is controlled.

4.2 Rate Outage

The user access to the system has been calculated in the previous section, but even if the user is selected, it may receive a rate that does not satisfy its SNR requirements snr^{th}, therefore going into a rate failure and causing an outage to that user. Thus, this section uses the distribution of the serving rate to characterize the rate outage, under a predefined ξ_{rate}.

Based on the opportunistic scheme philosophy to deliver service to the users, the serving SNR value is the maximum SNR over the active users in the system. Therefore, by using the SNR probability distribution function (pdf) of i.i.d. complex Gaussian channels [5][7]

$$f(x) = \sigma^2 e^{-(x\cdot\sigma^2)} \tag{4}$$

the cdf is then formulated as

$$F(x) = 1 - e^{-(x\cdot\sigma^2)} \tag{5}$$

and since the serving SNR is the maximum over all the users' SNR values, then the serving SNR cdf is stated as

$$FF(x) = (F(x))^N = \left[1 - e^{-(x\cdot\sigma^2)}\right]^N \tag{6}$$

therefore, considering the cdf of the serving rate, the minimum required rate snr^{th} for each user is achievable with a predefined rate outage ξ_{rate} as

$$\xi_{rate} = \left[1 - e^{-(snr^{th}\cdot\sigma^2)}\right]^N \tag{7}$$

where the values of snr^{th} and ξ_{rate} can be computed to meet any system objectives under the number of users N. Notice that the rate outage as seen from an information theory point-of-view, corresponds to the PER measure in networking theory, so that both terms can be used in a related manner [10] in a block fading scenario, as the PER states as

$$PER = \begin{cases} 0 & \text{if } \; SNR \geq snr^{th} \\ 1 & \text{if } \; SNR < snr^{th} \end{cases}$$

where the direct relation to ξ_{rate} is shown. With further manipulations, the snr^{th} from expression (7) formulates as

$$snr^{th} = \frac{1}{\lambda\sigma^2}\log_2\left(\frac{1}{1-\sqrt[N]{\xi_{rate}}}\right) \tag{8}$$

where the effect of all the involved parameters is shown, with $\lambda = \log_2(e) = 1.4427$.

4.3 System Outage

As previously explained, the opportunistic transmission process comes controlled by two different outage measures, but the total system performance has to be defined through a single parameter.

Notice that the two discussed kinds of outage are totally independent, as a user access to the channel happens when its SNR is the maximum over all the other users, but being the user with largest SNR does not guarantee that this SNR is larger than a given threshold snr^{th}. Therefore, the total outage ξ_{out} is defined as

$$\xi_{out} = 1 - (1-\xi_{access})\cdot(1-\xi_{rate}) \tag{9}$$

where the operator has another degree of freedom to optimize the system through both ξ_{access} and ξ_{rate}, as the commercial outage requirement can be imposed on the ξ_{out} global measure.

4.4 Maximum Scheduling Delay

Once the scenario outage has been defined, the maximum scheduling delay can be obtained, where the paper defines the delay as follows

Definition: Having a packet of length W bits corresponding to the i^{th} user, and waiting for transmission at the BS scheduler, the scheduling delay is defined as the maximum required time to make the packet to reach its destination.

Notice that this definition of delay incloses the delay resulting from the scheduling process (i.e. the opportunistic selection) together with the delay caused by the channel transmission (i.e. low data rate), therefore providing a general expression for delay in opportunistic schemes[1]. The smaller transmission unit is a packet, so that even the whole packet is transmitted or it fully remains at the BS buffer.

From previous section, the maximum number of time slots to select a user under a predefined delay outage was obtained as K, while this access provides a minimum rate of $R = \log_2(1+snr^{th})$ under a known rate outage. Therefore, the maximum scheduling delay, under an outage ξ_{out} is equal to the K access slots formulation in (3) as

$$\textit{maximum scheduling delay} = K = \frac{\log_2(\xi_{access})}{\log_2(1-1/N)} \quad (10)$$

showing the effect of the optimization variables. It is convenient to present a numerical example to avoid misleading conclusions for the reader, so that in a scenario with $N = 10$, $K = 25$, $\sigma^2 = 1$ and $snr^{th} = 1.3$ for each user, it results that $\xi_{access} = 7.2\%$ and $\xi_{rate} = 4.2\%$ are obtained, therefore each user is guaranteed a correct reception of its packet within a maximum delay of 25 slots and with a total outage of $\xi_{out} = 11.0\%$.

Notice that the maximum delay expression for opportunistic schemes has not been provided in the literature, due to the wireless propagation characteristics, but thanks to the considered outage scenario and the formulated cdf for rate and access processes, the maximum delay can now be characterized under a global ξ_{out} measure.

In the opportunistic scheduling policy only a single user does have access to each slot, therefore a more pragmatic system performance metric for the opportunistic schemes, is the user throughput normalized over each slot. With a system bandwidth B_w and t_s as the time slot (assumed to match the channel coherence time), the normalized minimum throughput defined in bits/slot states as

$$T = B_w t_s \frac{R}{K} = \frac{B_w t_s \log_2(1-1/N)\log_2(1+snr^{th})}{\log_2(\xi_{access})} \quad (11)$$

and plugging the expression in (8), the throughput is obtained in a closed form at the top of the next page with all the involved optimization parameters.

[1] Since this paper concerns about the scheduling delay, which is the most important kind of delay in the opportunistic scheme due to its multiuser service policy, both the buffer management and source statistics are not addressed [11].

4.5 Maximum Scheduling Jitter

Once the user access policy and the maximum scheduling delay are characterized, it is quite tractable to obtain an expression for the maximum jitter under a predefined system outage, where the jitter is

Definition: Having two consecutive packets of length W bits each, corresponding to the i^{th} user, and waiting for transmission at the BS scheduler. If the first packet is received at time t_1 while the second packet at time t_2, then the maximum jitter is defined [12] as the maximum difference between t_1 and t_2:

$$\textit{maximum jitter} = \max(t_2 - t_1) = \textit{maximum delay} \cdot t_s \quad (13)$$

Actually, this is a conservative expression for jitter, as it provides the maximum jitter, but it is required to characterize and design the communication system [12]. Plugging the expression (10) into the jitter formulation, gives the closed form expression of the maximum scheduling jitter.

As an example, for voice application the packets have to enter to the voice decoder in a sequentially synchronized process, so that the voice application seems to be continuous to the final user [6]. This is only obtained if the playout buffer is correctly designed, and without a specific jitter formulation as the one in (13), the viability of the opportunistic HSDPA-HDR schemes in delay constrained applications can be questioned.

5 Numerical Results

The performance of the proposed scheme is presented by Monte Carlo simulations, where we consider a single cell with a variable number of active users. The transmitter runs a modified HSDPA-HDR opportunistic technique, where the objective is to study the minimum QoS requirements in terms of rate and delay. A total system bandwidth of 1MHz with $t_s = 1$ msec are considered. A noise variance of $\sigma^2 = 1$ is also assumed.

First of all, the paper studies the derived outages to test their certainty by simulations, so that in figure (1) a scenario with 15 active users is considered, and where the resulting K value is plotted for several values of ξ_{access}. To provide the reader with more insight on the relevance of the K parameter, the fitting to the integers of K is also shown in the figure, as K can only take integer values in real systems. The plot also shows how the theoretical integer values perfectly match the simulated ones.

Regarding the rate outage that the opportunistic systems incur due to the fading channel characteristics, figure (2) plots the ξ_{rate} parameter for different values of minimum rate. The results exhibit how a higher rate outage ξ_{rate} is obtained when the user requirement increases, which is also evident from the

$$T = \frac{B_w t_s \log_2(1-1/N)\ \log_2\left(1+\frac{1}{\lambda\sigma^2}\log_2\left(\frac{1}{1-\sqrt[N]{\xi_{rate}}}\right)\right)}{\log_2(\xi_{access})} \quad (12)$$

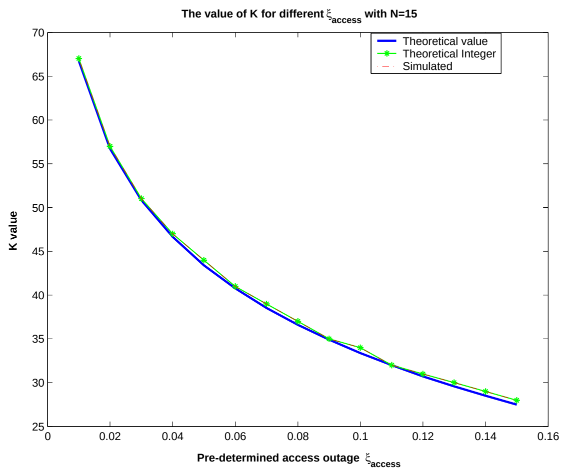

Figure 1: The system performance with delay outage.

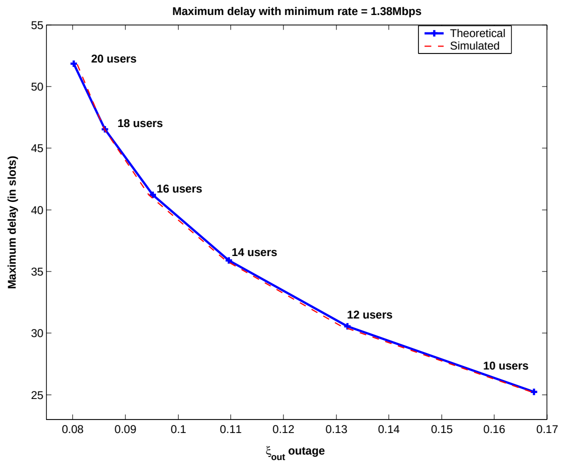

Figure 3: The system maximum scheduling delay.

mathematical formulation in (7). The simulations show how the theoretically obtained results perfectly match the simulated values. Two number of active users are considered in the cell, to show the effect of the multiuser gain on the outage performance, as a higher number of available users, provides more freedom to the scheduler to choose the best user to meet its requirements, so that lower outage is expected.

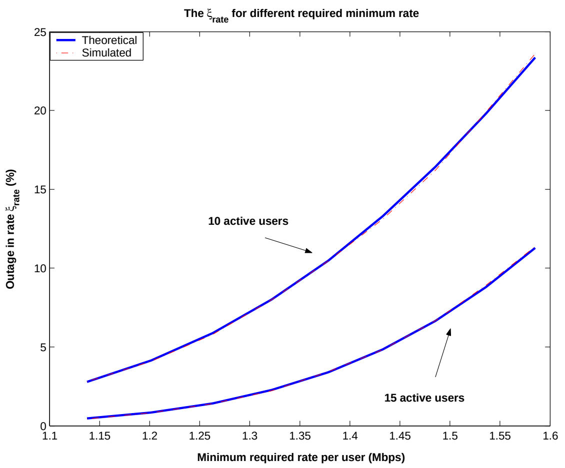

Figure 2: The system performance with rate outage.

Concerned with the main motivation of this paper, the maximum scheduling delay performance is plotted in figure (3) for different values of outage ξ_{access}, where it is shown how the maximum delay is decreased for a larger allowed outage. Notice that a variable number of active users is available in the scenario, each one corresponding to a different outage value. A packet length of $W = 160$ bytes is regarded in the simulations.

As already commented, a more pragmatic system metric in opportunistic schemes is the normalized throughput over the time slots, as a user is not serviced over all the time slots. Regarding the normalized system throughput in equation (12), figure (4) exhibits its results for different number of active users. It displays how a lower normalized throughput is obtained as more users are available in the system, as each serviced user has to wait for longer time until it is again supplied with service, thus decreasing its normalized throughput.

By considering a different scenario where the paper fixes a given total outage $\xi_{out} = 10\%$ and tests for the maximum scheduling jitter performance when changing the number of users, but all of them under the same value of outage. The results are plot in figure (5), where an amazing result is obtained. Even it denotes the maximum jitter under outage performance, which is per-se an interesting result, but it also shows that there is an optimum number of users where each outage can be satisfied, with the minimum value for the maximum jitter. This is an interesting tool for network dimensioning as it indicates the optimal number of users in each cell for the best jitter performance. The obtained results are explained by the opportunistic transmission policy, where more users decrease the rate outage as previously seen in figure (2), but at the same time, a higher number of users means that each user has to wait for a longer time to have access to the network. The figure reflects that a large number of users is beneficial until a given point (12 users in the plot) due to the multiuser gain; but that a further increase in the number of users, does not compensate for their disadvantage in access delay. This last result motivates the need for an adaptive Call Admission Control (CAC) for its implementation in practical systems, which will be considered in future work.

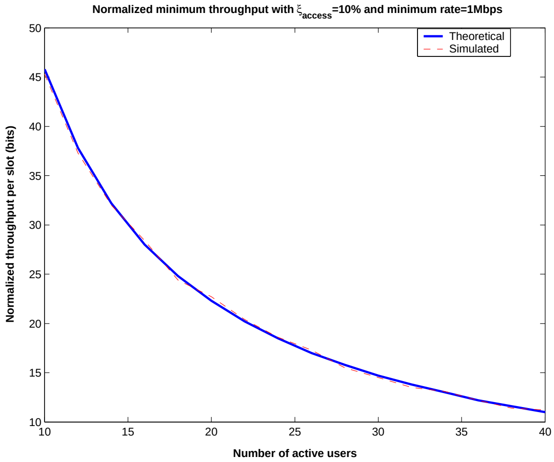

Figure 4: The normalized throughput per slot.

6 Summary and Conclusions

Within a practical transmission system for commercial operators, a modified HSDPA-HDR opportunistic scheme is set up with each user asking for a minimum rate to satisfy its QoS, where a predefined system outage is allowed. The outage comes from two sources, even through the users access process to the system resources, and/or due to the fading channel characteristics. The mathematical solutions for both cases are obtained, and a general outage measure is proposed.

Once the outage scenario statistics are obtained, the maximum scheduling delay that suffers a packet waiting for transmission is calculated, and given in a closed form solution. As a practical system indicator, the maximum system jitter is also stated for the considered scenario.

Simulations show the benefit of the obtained results for different environments, and the effect of the several optimization variables is studies, with a perfect match between the theoretically obtained equations and the simulated scenarios.

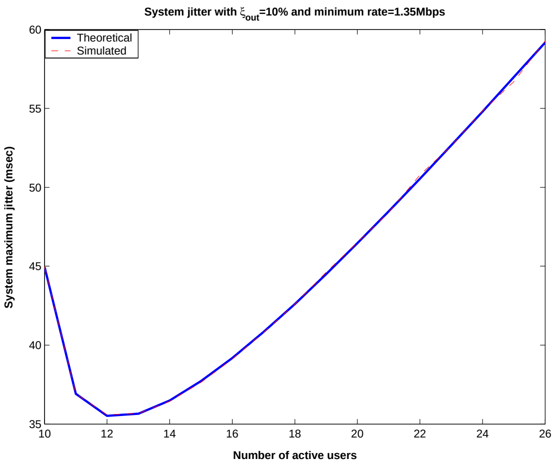

Figure 5: The system maximum jitter in outage scenarios.

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