

# RESOURCE CONTROL FOR HYBRID CODE AND TIME DIVISION SCHEDULING

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**Abstract** - We present a model, based on economic theory, for efficient and robust resource control in hybrid code and time division scheduling wireless systems. Based on this model, we propose procedures for combined rate allocation and time slot allocation to achieve efficient utilization of wireless resources, while taking into account user requirements. These procedures can be applied using a class-based framework, which allows simple implementation, and where users select a service class reflecting their valuation for the average throughput and for the percentage of time slots in which they can transmit data.

**Keywords** - resource management, utility, economic efficiency, service differentiation

## I. INTRODUCTION

Efficient spectrum and wireless resource utilization is one of the most important issues in current and future wireless systems, due to the limited capacity of such systems compared to wired networks. Many of these systems, such as Wideband CDMA (Code Division Multiple Access), will support both code and time division scheduling. Combination of these two scheduling schemes can be used to efficiently utilize resources for both streaming applications, which require continuous transmission of data, and best-effort applications, which generate bursty traffic and can tolerate delays.

Time division scheduling has the advantage of supporting higher transfer rates for the same energy per transmitted bit, compared to code division scheduling, but requires time synchronization between stations and has the disadvantage of non-continuous transmission, which results in bursty traffic. Indeed, [1] shows that in a hybrid code and time division scheduling system supporting real-time (delay intolerant) and non real-time (delay tolerant) traffic, both with fixed target bit-energy-to-noise-density ratio, the aggregate transmission rate of non real-time traffic is maximized if it is scheduled so that only one non real-time source sends traffic in each time slot. Unlike time division multiplexing, code division scheduling supports continuous data transmission, but has the disadvantage of lower instantaneous bit rates due to higher interference.

The shared channels and the common packet channel (in the uplink) of WCDMA typically use both time division and code division scheduling. In the downlink, orthogonal codes

are shared between many users in a time division manner, i.e. there may be many common packet channels per cell, each having a different bit rate, that are shared among many users in a time division manner. On the other hand, dedicated channels typically use code division scheduling, hence in the downlink one orthogonal code is consumed for each user of a dedicated channel. Indeed, for dedicated channels the bit rate can change during transmission, but remains constant within a single frame that has a minimum duration of 10 ms, and the orthogonal code must be allocated according to the highest requested bit rate.

In this paper we present a model for efficient and robust resource control in hybrid code and time division scheduling wireless systems, which is based on economic theory and extends the work in [2], which considered pure code division multiplexing. Based on this model, we propose procedures for combined rate allocation and time slot allocation to achieve efficient utilization of wireless resources, while taking into account user requirements; the latter are modelled using utility functions. The procedures can be applied using a class-based framework, hence allow simple implementation, where users select a service class reflecting their valuation for the average throughput and for the percentage of time slots in which they can transmit.

Our work differs from the work of [1], which also considers hybrid code and time division scheduling systems, in that our model considers the joint control of the transmission rate and the percentage of time slots in which users are allowed to send, in order to achieve efficient utilization of resources according to user requirements. Moreover our work differs from other work that investigates the application of economic theory to wireless systems, such as [3], [4], [2], [5], in that we consider systems with simultaneous support for both code and time division scheduling.

The rest of the paper is organized as follows. In Section II we discuss resource usage in the uplink of hybrid code and time division scheduling systems. In Section III we present our model for the joint control of the transmission rate and the percentage of time slots in which a user can transmit, and in Section IV we discuss the application of our model using a class-based service differentiation framework. In Section V we present numerical experiments demonstrating the application of the proposed model. Finally, in Section VI we conclude the paper.

## II. RESOURCE USAGE MODEL

Consider the uplink of a single CDMA cell. Note, however, that the results can be extended to the multiple cell case by considering the inter-cell interference coefficient [6]. Let  $W$  be the chip rate. The bit-energy-to-noise-density ratio at the base station is given by [6], [7]

$$\left(\frac{E_b}{N_0}\right)_i = \frac{W}{r_i} \frac{g_i p_i}{\sum_{j \neq i} g_j p_j + \eta}, \quad (1)$$

where  $r_i$  is the transmission rate,  $p_i$  is the transmission power,  $g_i$  is the path gain between the base station and mobile  $i$ , and  $\eta$  is the power of the background noise at the base station. The ratio  $W/r_i$  is the spreading factor or processing gain for mobile  $i$ .

The value of the bit-energy-to-noise-density ratio  $(E_b/N_0)_i$  corresponds to the signal quality, since it determines the bit error rate,  $BER$  [6], [7]. Under the assumption of additive white Gaussian noise,  $BER$  is a non-decreasing function of  $E_b/N_0$ , that depends on the multipath characteristics, and the modulation and forward error correction (FEC) algorithms. Let  $\gamma_i$  be the target bit-energy-to-noise-density ratio required to achieve a target  $BER$ . This target is given to closed-loop power control, which adjusts the transmission power in order to achieve it.

If we assume perfect power control, in which case  $(E_b/N_0)_i = \gamma_i$ , and solve the set of equations given by (1) for each mobile  $i$ , we get [7], [8]

$$g_i p_i = \frac{\eta \alpha_i}{1 - \sum_j \alpha_j}, \quad (2)$$

where the load factor  $\alpha_i$  is given by

$$\alpha_i = \frac{1}{\left(\frac{W}{r_i \gamma_i} + 1\right)}.$$

The power levels given by the set of equations (2) for  $i \in I$ , where  $I$  is the set of mobiles, are the minimum such that the target bit-energy-to-noise-density ratios  $\{\gamma_i\}$  are met. Since the power  $p_i$  can take only positive values, from (2) we get

$$\sum_i \alpha_i < 1. \quad (3)$$

The last equation illustrates that the uplink is interference-limited: Even when they have no power constraints, mobile hosts cannot increase their power with no bound, due to the increased interference they would cause to the other mobiles. If (3) is violated, then the target  $\{\gamma_i\}$  cannot be met for all mobiles.

For hybrid code and time division multiplexing, the constraint on resource usage in the uplink becomes

$$\sum_i \alpha_i \varrho_i < 1, \quad (4)$$

where  $\alpha_i = \frac{r_i \gamma_i}{W + r_i \gamma_i}$  is the resource usage for the uplink in pure code division multiplexing systems, and  $\varrho_i$  is the percentage of time slots in which user  $i$  sends traffic.

The constraint (4) can be extended to take into account the case of limited transmission power at mobile hosts, imperfect power control, and inter-cell interference; this is done by considering an interference margin  $I_{margin}$  [9], which limits the maximum utilization  $\rho$  that can be achieved. In this case, (4) becomes

$$\sum_i \alpha_i \varrho_i < \rho, \quad \text{where } \rho = \frac{I_{margin} - 1}{I_{margin}}. \quad (5)$$

## III. RESOURCE CONTROL MODEL

In this section we first propose a utility model for elastic users that value both the average throughput with which they can transmit and the percentage of time slots in which they can transmit; note that the two are not identical, since the user can transmit a different amount of data, i.e. have a different transmission rate, in different time slots. Utility functions are widely used for capturing user and application requirements, and give the level of satisfaction for a given level of service. Then, considering the results for resource usage discussed in the previous section, we present our model for efficient resource control in hybrid code and time division scheduling systems.

The average throughput for user  $i$  is given by the product  $\varrho_i r_i P_i(\gamma_i)$ , where  $\varrho_i$  is percentage of time slots in which user  $i$  can send data,  $r_i$  is his average transmission rate in each slot, and  $P_i(\gamma_i)$  is the probability of successful packet transmission. Hence, user  $i$ 's valuation for the average throughput can be written as

$$U_i(\varrho_i r_i P_i(\gamma_i)).$$

The factor encoding user  $i$ 's valuation for the percentage of time slots he is allowed to transmit can be expressed as

$$V_i(\varrho_i),$$

where  $\varrho_i$  is percentage of time slots in which user  $i$  can transmit. Note that this factor captures solely the average percentage of time slots a user can transmit, and is independent of their distribution.

Based on the above, the overall utility for a user that values both the average throughput and the percentage of time slots in which he can transmit data can be expressed as

$$U_i(\varrho_i r_i P_i(\gamma_i)) + V_i(\varrho_i),$$

where the first factor  $U_i$  encodes user  $i$ 's valuation for the average throughput and the second factor  $V_i$  encodes user  $i$ 's valuation for the percentage of time slots in which he can transmit. The above model assumes an additive relationship between the two factors; another alternative is to have a multiplicative relationship between the two factors; the conclusions obtained considering such a multiplicative model are qualitatively the same as those obtained for the additive model that we consider in this paper.

The user's net utility maximization problem is

$$\begin{aligned} & \text{maximize} && U_i(\varrho_i r_i P_i(\gamma_i)) + V_i(\varrho_i) - \lambda \alpha_i \varrho_i \quad (6) \\ & \text{over} && r_i \geq 0, \gamma_i \geq 0, \varrho_i \geq 0, \end{aligned}$$

where  $\lambda$  is the shadow price for the wireless resource constraint (5).

Although the general form of the above user utility can have a complex non-concave structure, hence the global problem of maximizing the sum of all utilities (social welfare) can have a non-trivial structure for which the Lagrangian method for finding the maximum cannot be applied, through experimentation with a range of user utility expressions we have found that for a wide range of user utilities the Lagrangian method can indeed be applied. In this case, the social welfare can be achieved in a decentralized manner, by iteratively adjusting the shadow price  $\lambda$  and independently solving each user problem (6). The iterative adjustment of  $\lambda$  can involve decreasing the value of  $\lambda$  when the constraint in (5) is not tight, i.e. when the demand for resources is less than the supply, and increasing its value when the constraint is violated, i.e. when the demand for resource is greater than the supply.

Moreover, as we discuss in Section IV, the above model can be applied using a class-based service differentiation framework, where users select a particular class for their valuation of the average throughput and for the percentage of time slots in which they can transmit data, and the network controls the transmission rate and time slot allocation based on the network traffic load; such an approach has the advantage of not requiring the implementation of complex mechanisms at the mobile hosts.

Based on the first order conditions of (6), if we take the partial derivatives with respect to  $r, \gamma, \varrho$  of the objective function in (6) and equating them with zero we get

$$U_i'(\varrho_i^* r_i^* P_i(\gamma_i^*)) P_i(\gamma_i^*) = \lambda \frac{W \gamma_i^*}{(W + r_i^* \gamma_i^*)^2}, \quad (7)$$

$$U_i'(\varrho_i^* r_i^* P_i(\gamma_i^*)) P_i'(\gamma_i^*) = \lambda \frac{W}{(W + r_i^* \gamma_i^*)^2}, \quad (8)$$

$$U_i'(\varrho_i^* r_i^* P_i(\gamma_i^*)) r_i^* P_i(\gamma_i^*) + V_i'(\varrho_i^*) = \lambda \frac{r_i^* \gamma_i^*}{W + r_i^* \gamma_i^*}, \quad (9)$$

From (7) and (8) we find that the optimal  $\gamma_i^*$  is independent of the price  $\lambda$  and the user utility, and satisfies

$$P_i(\gamma_i^*) = P_i'(\gamma_i^*) \gamma_i^*. \quad (10)$$

The last expression shows that the selection of the optimal signal quality is independent of both the user's utility and the price, and depends only on the dependence of the packet success ratio on the target signal quality. This result is similar to the case of best-effort traffic where users value only the average throughput [2], and allows us to decompose the utility maximization problem (6) into two simpler problems: one problem involving the selection of the optimal signal quality  $\gamma_i^*$ , and one problem involving the selection of the

optimal transmission rate  $r_i^*$  and the optimal percentage of time slots  $\varrho_i^*$  in which a user can transmit data. The first problem is identical to the one discussed in [2], hence in the remainder of the paper we focus on the second problem.

From (9) and (7) we have

$$\begin{aligned} \lambda \frac{W r_i^* \gamma_i^*}{(W + r_i^* \gamma_i^*)^2} + V_i'(\varrho_i^*) &= \lambda \frac{r_i^* \gamma_i^*}{W + r_i^* \gamma_i^*} \Rightarrow \\ V_i'(\varrho_i^*) &= \lambda \frac{(r_i^* \gamma_i^*)^2}{(W + r_i^* \gamma_i^*)^2}. \quad (11) \end{aligned}$$

From (7) and (11) we have

$$U_i'(\varrho_i^* r_i^* P_i(\gamma_i^*)) \frac{P_i(\gamma_i^*) r_i^{*2} \gamma_i^*}{W} = V_i'(\varrho_i^*). \quad (12)$$

The last equation gives the tradeoff between the optimal transmission rate  $r_i^*$  and the optimal percentage of time slots  $\varrho_i^*$  that user  $i$  can transmit data. Note that this tradeoff depends solely on the utility factors  $U_i, V_i$ , and is independent of the network traffic load; however, the particular pair which is optimal for a given traffic scenario will depend on the network traffic load through the shadow price  $\lambda$ , and will satisfy (11).

#### IV. APPLICATION

The model presented in the previous section suggests how to optimally set the three control variables in hybrid code and time division multiplexing systems: the target bit-energy-to-noise-density ratio based on (10), and the transmission rate and percentage of time slots in which a user can transmit data, based on (11) and (12). The first procedure for adjusting the target bit-energy-to-noise-density ratio is performed by outer-loop power control, and is identical to the corresponding procedure in the pure code division multiplexing case discussed in [2].

The adjustment of the other two variables can be achieved in a class-based framework where the network supports a limited set of classes, each corresponding to a particular valuation for the average throughput and a particular valuation for the percentage of time slots a user can transmit data. As a specific example, consider the following expression for the throughput valuation factor

$$U_i(x_i) = 1 - e^{-u_i x_i}, \quad (13)$$

where  $x_i$  is the average throughput, and the following expression for the valuation factor related to the percentage of time slots  $\varrho_i$  a user can transmit data

$$V_i(\varrho_i) = 1 - e^{-v_i \varrho_i}. \quad (14)$$

A network provider can offer a small set of possible values for  $u_i$ , each corresponding to a different throughput class, and  $v_i$ , each corresponding to a different class related to the percentage of time slots a user can transmit data. Each user selects, at the subscription or the connection setup phase, a particular class, which corresponds to particular values

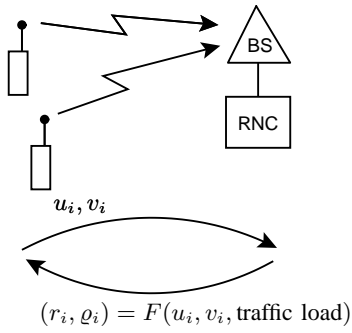


Fig. 1

Class-based implementation of the proposed model. Each user selects a class corresponding to particular values for  $u_i, v_i$ . Based on this selection, and taking into account the network load, the RNC computes the optimal transmission rate and percentage of time slots the user can transmit.

of the parameters  $u_i, v_i$ , Fig. 1. The network, through the Radio Network Controller (RNC) in the case of 3G wireless systems based on WCDMA, and based on the traffic load, selects for each user the transmission rate and the percentage of time slots he can transmit, according to (11) and (12).

## V. NUMERICAL INVESTIGATIONS

In this section we present numerical investigations demonstrating the model proposed in the previous sections.

We assume that users have a utility function that is the sum of the two factors given by (13) and (14). Fig. 2 shows the throughput factor for the two values of parameter  $u_i$  in (13) that we consider. Fig. 3 shows the factor related to the percentage of time slots a user is allowed to transmit, for the two values of parameter  $v_i$  in (14) that we consider.

In the case of additive white Gaussian noise and a non-fading channel, the bit error rate for DPSK (Differential Phase Shift Keying) modulation is [10]

$$BER(\gamma) = 0.5e^{-\gamma}.$$

If there is no error correction, and bit errors are independent and are all detected, then the packet success probability  $P(\gamma)$ , which we assume to be the same for all mobiles, is given by

$$P(\gamma) = (1 - BER(\gamma))^L,$$

where  $L$  is the number of bits in one packet. The values of the other parameters are shown in Table 1.

Figure 4 shows the tradeoff between the transmission rate  $r$  and the percentage of time slots  $\rho$  a user is allowed to transmit; this tradeoff is computed from (12), and is independent of the network traffic load. Observe that for both small and large values of the transmission rate, the percentage of time slots  $\rho$  a user should be allowed to send

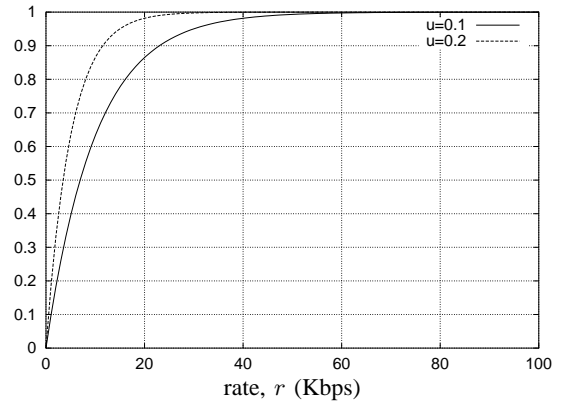


Fig. 2

Throughput utility factor given by (13), for  $u = 0.1, 0.2$ .

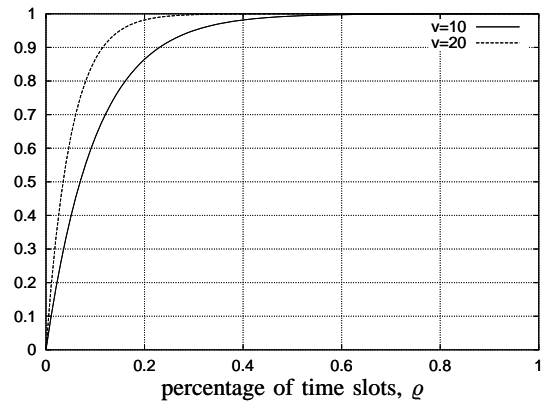


Fig. 3

Utility factor related to the percentage of time slots given by (13), for  $v = 10, 20$ .

is close to one. The former behaviour, for small values of the transmission rate, is due to the right-hand side of (11) obtaining small values, hence the derivative  $V'_i$  should be small, which is the case for large values of  $\rho$  due to the concavity of  $V_i$ , Fig. 3. The latter behaviour, for large values of the transmission rate, is due to the left-hand side of (12) obtaining small values due to the concavity of the throughput factor  $U_i$ , Fig. 2, hence as before the derivative  $V'_i$  should be small, which is the case for large values of  $\rho$ .

Fig. 5 shows the optimal transmission rate for different traffic loads, expressed as the number of users. As expected, a higher load results in a smaller transmission rate for each user. From this figure, also observe that the optimal transmission rate depends on the user preferences, expressed through the utility function. In the class-based approach described in Section IV, a network provider would determine the optimal transmission rate, based on the number and type of users, from Fig. 5, and then the optimal percentage of time slots a user is allowed to transmit, from Fig. 4.

Table 1  
Parameters for the numerical investigations.

parameter	value
chip rate, $W$	3.84 Mcps
load, $\rho$	60%
$BER(\gamma)$ (DPSK)	$0.5e^{-\gamma}$
bits per pkt, $L$	60
$\gamma^*$ , from (10)	5
throughput factor	$U(x) = 1 - e^{-ux}$ , $u = 0.1, 0.2$
time slot factor	$V(\varrho) = 1 - e^{-u\varrho}$ , $v = 10, 20$

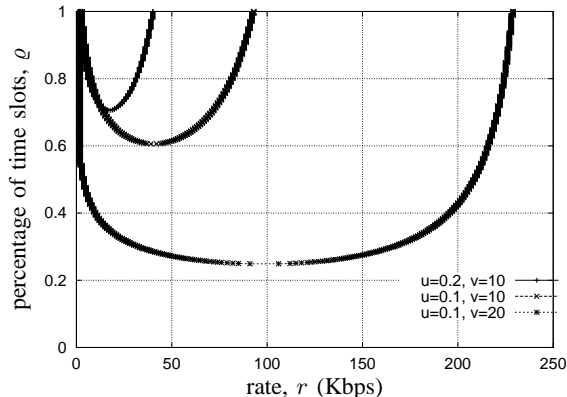


Fig. 4

Tradeoff between transmission rate and percentage of time slots a user can transmit.

## VI. CONCLUSION

We have presented a model for efficient resource control in hybrid code and time division scheduling systems. Our approach is based on economic theory and utility functions for capturing user preferences, and addresses the issue of how the transmission rate and the percentage of time slots that users can transmit should be jointly controlled in order to achieve efficient utilization of network resources. Finally, our approach can be applied using a class-based service differentiation framework, where users select a throughput class reflecting how much they value their average throughput, and a class related to the percentage of time slots they are allowed to transmit. Possible further work includes evaluating our proposal in the case of fading channels that are different for each user, extending the model to the downlink, and considering utility functions where users value, in addition to the average throughput, the packet loss probability; work related to the latter is presented in [11].

## ACKNOWLEDGEMENTS

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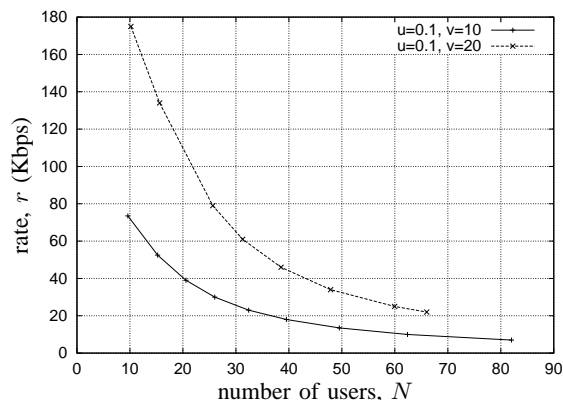


Fig. 5

Optimal transmission rate for a different number of users.

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