

Resource Control for Hybrid Code and Time Division Scheduling Wireless Systems*

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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. An important and novel feature of the model is that it captures the combined effects of the transmission rate, the signal quality, and the percentage of time slots a user can transmit in, on the overall efficiency of the wireless system. Based on this model, we propose procedures for combined rate 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 that allows simple implementation and requires simple communication between the network and its users, which 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, service differentiation, economic efficiency, utility

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1 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 in the presence of applications with different Quality of Service (QoS) requirements, such as 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 a 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. As the results in the current paper demonstrate, the above approach is not optimal when users value the ability to send in a smoother fashion, i.e. in consecutive time slots. Unlike time division multiplexing, code division scheduling supports continuous data transmission, but has the disadvantage of lower instantaneous bit rates due to higher interference. Hence, there is a tradeoff between satisfying user requirements in terms of the ability to send data in a smooth fashion, and increasing the aggregate throughput of the system. An objective of the model presented in the current paper is to capture this tradeoff.

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 milliseconds, 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. The approach builds on a model for resource usage in code and time division scheduling systems. An important and novel feature of the model is that it captures the combined effects of the transmission rate, the signal quality, and the percentage of time slots in which a user can transmit data, on the overall efficiency of the wireless system. Moreover, the model takes into account user and application QoS requirements, which are expressed using utility functions. Based on this model, we propose procedures for combined rate and time slot allocation which, combined with power control, can achieve efficient utilization of wireless resources, hence enabling cross-layer optimization of procedures operating at different layers. Finally, we discuss how the procedures can be applied using a class-based framework that allows simple implementation and requires simple communication between the network and its users, which select a service class reflecting their valuation for the average throughput they can achieve, 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; on the other hand, the work of [1] considers the objective of maximizing the aggregate system throughput. Moreover our work differs from other work that investigates the application of economic theory to wireless systems, such as [3, 4, 2, 5, 6] and the references therein, 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 2 we discuss resource usage in the uplink of hybrid code and time division scheduling systems. In Section 3 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 4 we discuss the application of our model using a class-based service differentiation framework. In Section 5 we present numerical experiments demonstrating the application of the proposed model. Finally, in Section 6 we conclude the paper.

2 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 [7]. Let W be the chip rate. The bit-energy-to-noise-density ratio at the base station is given by [7, 8]

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

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 η 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* [7, 8]. 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 γ_i be the target bit-energy-to-noise-density ratio, or signal quality, 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 [8, 9]

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

where the load factor α_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

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

Hence, α_i expresses the resource usage for user i . 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.

The constraint (3) is applicable to a pure code division multiplexing system, where the control variables are the transmission rate and signal quality for each mobile. If we further consider the ability to schedule the transmission of mobiles such that they transmit only in some percentage of time slots within a large time frame, then the constraint on resource usage in the uplink becomes

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

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

The constraint (4) can be extended to take into account the case of limited transmission power at mobile hosts, imperfect power control, variations of the channel characteristics due to shadowing and Rayleigh fading, and inter-cell interference; this is done by considering an interference margin I_{margin} [10], which limits the maximum utilization ρ that can be achieved. In this case, (4) becomes

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

The above analysis referred to the uplink. In the downlink, the constrained resource is the total transmission power at the base station, which can lead to a resource control model that is different from the one in the uplink. Nevertheless, one can show, see [10], that for resource dimensioning and network planning the downlink constraint can be approximated by an inequality similar to (5)

$$\sum_i \alpha_i < \rho^{DL},$$

where $\rho^{DL} < 1$ depends on the total base station power, the noise, the average attenuation from the base station to the mobiles, the average downlink orthogonality factor, and the average inter-cell interference. Hence, if we assume the resource constraint given in the last equation, we can apply the models and results presented in the following sections to the downlink as well.

3 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. 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 $\phi_i r_i P_i(\gamma_i)$, where ϕ_i is percentage of time slots in which user i can send data, r_i is his transmission rate in each slot, and $P_i(\gamma_i)$ is the probability of successful packet transmission; the latter depends on the bit error rate, hence on the target bit-energy-to-noise-density ratio (signal quality). Based on the above, user i 's valuation for the average throughput can be written as

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

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

$$V_i(\phi_i),$$

where ϕ_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 in, and does not account for the distribution of these time slots. The percentage of time slots in which a user can transmit is related to the maximum channel access delay, which together with the queuing delay, the transmission delay, and the propagation delay contributes to the end-to-end delay in the packet network, hence relates to the quality of service experienced by the user.

In the next two subsections we consider the case where the overall utility of a user has an additive and a multiplicative dependence on the two factors U_i and V_i . The additive dependence applies to the case where the user's valuation for the average throughput and the percentage of time slots in which he can transmit are independent. On the other hand, as we will discuss in Section 3.2, with a multiplicative dependence the two valuations are not independent.

3.1 Additive dependence on utility factors

Next we consider the case where the overall utility for a user that values both the average throughput and the percentage of time slots in which he can transmit data is an additive function of the two factors U_i and V_i introduced above, hence can be expressed as

$$U_i(\phi_i r_i P_i(\gamma_i)) + V_i(\phi_i).$$

The above model assumes that a user's valuation for his average throughput is independent of his valuation for the average number of time slots in which he can transmit data.

The global problem of maximizing the aggregate utility (social welfare) is

$$\begin{aligned} \text{maximize} \quad & \sum_i [U_i(\phi_i r_i P_i(\gamma_i)) + V_i(\phi_i)] \end{aligned} \quad (6)$$

$$\text{over} \quad r_i \geq 0, \gamma_i \geq 0, \phi_i \geq 0$$

$$\text{subject to} \quad \sum_i \phi_i \alpha_i < \rho. \quad (7)$$

Although the general form of the above user utilities 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 necessarily be applied, through experimentation we have found that for a wide range of user utilities the Lagrangian method can indeed be applied. Hence, in the remainder of this paper we focus on discussing the conclusions if this assumption holds, and the resulting procedures for achieving efficient wireless channel utilization.

The Lagrangian for (6) is

$$\mathcal{L} = \sum_i [U_i(\phi_i r_i P_i(\gamma_i)) + V_i(\phi_i)] + \lambda(\rho - \sum_i \phi_i \alpha_i), \quad (8)$$

where λ is the shadow price for the wireless resource constraint (7). Based on the first order conditions for the above optimization problem, if we take the partial

derivatives with respect to r, γ, ϕ of (8) and equate them with zero we get

$$U'_i(\phi_i^* r_i^* P_i(\gamma_i^*)) P_i(\gamma_i^*) = \lambda \frac{W \gamma_i^*}{(W + r_i^* \gamma_i^*)^2}, \quad (9)$$

$$U'_i(\phi_i^* r_i^* P_i(\gamma_i^*)) P'_i(\gamma_i^*) = \lambda \frac{W}{(W + r_i^* \gamma_i^*)^2}, \quad (10)$$

$$U'_i(\phi_i^* r_i^* P_i(\gamma_i^*)) r_i^* P_i(\gamma_i^*) + V'_i(\phi_i^*) = \lambda \frac{r_i^* \gamma_i^*}{W + r_i^* \gamma_i^*}, \quad (11)$$

From (9) and (10) we find that the optimal signal quality γ_i^* satisfies

$$P_i(\gamma_i^*) = P'_i(\gamma_i^*) \gamma_i^*. \quad (12)$$

The last expression shows that the selection of the optimal signal quality is independent of both the user's utility and the shadow 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 global maximization problem (6) into two simpler problems: one problem involving the selection of the optimal signal quality γ_i^* , and another problem involving the selection of the optimal transmission rate r_i^* and the optimal percentage of time slots ϕ_i^* in which user i 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 (11) and (9) we have

$$\begin{aligned} \lambda \frac{W r_i^* \gamma_i^*}{(W + r_i^* \gamma_i^*)^2} + V'_i(\phi_i^*) &= \lambda \frac{r_i^* \gamma_i^*}{W + r_i^* \gamma_i^*} \Rightarrow \\ V'_i(\phi_i^*) &= \lambda \frac{(r_i^* \gamma_i^*)^2}{(W + r_i^* \gamma_i^*)^2}. \end{aligned} \quad (13)$$

From (9) and (13) we have

$$U'_i(\phi_i^* r_i^* P_i(\gamma_i^*)) \frac{P_i(\gamma_i^*) r_i^{*2} \gamma_i^*}{W} = V'_i(\phi_i^*). \quad (14)$$

The last equation gives the tradeoff between the optimal transmission rate r_i^* and the optimal percentage of time slots ϕ_i^* in which 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 λ , and will satisfy (13).

One approach for determining the shadow price for which the optimal in (6) is achieved is to use a tatonnement procedure as follows: the price λ is increased when the resource constraint (7) is violated, and is decreased when the constraint (7) is not tight, i.e. it contains a strict inequality. At the optimal, the constraint (7) will be tight.

3.2 Multiplicative dependence on utility factors

The above model assumed an additive relationship between the factors for the average throughput and the percentage of time slots in which a user can transmit data. If we consider a multiplicative relation between the two factors, then we have the following expression for a user's utility

$$U_i(\phi_i r_i P_i(\gamma_i)) V_i(\phi_i).$$

According to the above expression, a user's valuation for the average number of time slots in which he can transmit is not independent of his average throughput, as in the case of an additive relationship between the two utility factors. In particular, for a higher average throughput, the same increase of the average time slots in which a user can transmit yields a higher increase of the overall utility, compared to the case of a lower valuation for the average throughput.

The global problem of maximizing the aggregate utility is

$$\begin{aligned} & \text{maximize} && \sum_i [U_i(\phi_i r_i P_i(\gamma_i)) V_i(\phi_i)] && (15) \\ & \text{over} && r_i \geq 0, \gamma_i \geq 0, \phi_i \geq 0 \\ & \text{subject to} && \sum_i \phi_i \alpha_i < \rho, \end{aligned}$$

Taking the partial derivatives, with respect to r, γ, ϕ , of the objective function in (15) and equating them with zero gives:

$$U'_i(\phi_i^* r_i^* P_i(\gamma_i^*)) P_i(\gamma_i^*) V_i(\phi_i^*) = \lambda \frac{W \gamma_i^*}{(W + r_i^* \gamma_i^*)^2}, \quad (16)$$

$$U'_i(\phi_i^* r_i^* P_i(\gamma_i^*)) P'_i(\gamma_i^*) V_i(\phi_i^*) = \lambda \frac{W}{(W + r_i^* \gamma_i^*)^2}, \quad (17)$$

$$U'_i(\phi_i^* r_i^* P_i(\gamma_i^*)) r_i^* P_i(\gamma_i^*) V_i(\phi_i^*) + U_i(\phi_i^* r_i^* P_i(\gamma_i^*)) V'_i(\phi_i^*) = \lambda \frac{r_i^* \gamma_i^*}{W + r_i^* \gamma_i^*}. \quad (18)$$

From (16) and (17) we find that the optimal γ_i^* satisfies the following.

$$P_i(\gamma_i^*) = P'_i(\gamma_i^*) \gamma_i^*.$$

Hence, as with the additive utility model, 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 rate on the target signal quality.

From (18) and (16) we have

$$\begin{aligned} \lambda \frac{W r_i^* \gamma_i^*}{(W + r_i^* \gamma_i^*)^2} + U_i(\phi_i^* r_i^* P_i(\gamma_i^*)) V'_i(\phi_i^*) &= \lambda \frac{r_i^* \gamma_i^*}{W + r_i^* \gamma_i^*} \Rightarrow \\ U_i(\phi_i^* r_i^* P_i(\gamma_i^*)) V'_i(\phi_i^*) &= \lambda \frac{(r_i^* \gamma_i^*)^2}{(W + r_i^* \gamma_i^*)^2}. \end{aligned} \quad (19)$$

From (16) and (19) we have

$$U'_i V_i \frac{P_i r_i^{*2} \gamma_i^*}{W} = U_i V'_i. \quad (20)$$

The last expression gives the tradeoff between the optimal transmission rate and the optimal percentage of time slots in which a user can transmit data, when there is a multiplicative dependence on the two corresponding utility factors.

4 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 (12), and the transmission rate and percentage of time slots in which a user can transmit data, based on (13) and (14). This cross-layer interdependence of control mechanisms is depicted in Figure 1. 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]. In particular, the target signal quality is increased or decreased in order to achieve the equality in (12); this differs from current outer-loop power control procedures, which increase (or decrease) the signal quality depending on whether the measured packet error rate is larger (or smaller) than a target packet error rate, which is typically 10-20% for non real-time services and 1% for real-time services, [10]. Also, observe in Figure 1 that the target signal quality determined by outer loop control is given as input to both the rate and percentage of time slot control procedures, and to the closed-loop power control procedure; note that the operation of the latter is not affected by the proposed models.

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 for the percentage of time slots in which a user can transmit data. As a specific example, consider the following expression for the average throughput valuation factor

$$U_i(x_i) = 1 - e^{-u_i x_i}, \quad (21)$$

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

$$V_i(\phi_i) = 1 - e^{-v_i \phi_i}. \quad (22)$$

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 of the parameters u_i, v_i , Figure 2. Based on the traffic load and the set of active mobiles, the network can select for each class the transmission rate and the percentage of time slots users of this class can transmit, according to (13) and (14); in these equations, the optimal signal quality γ^* is known from the outer loop power control procedure, which operates at the Radio Network Controller (RNC) of WCDMA networks. Indeed, the aforementioned functionality can be implemented within the cell-specific packet scheduler that is located at the Radio Network Controller (RNC) of WCDMA networks [10], whose responsibility is to allocate the capacity between mobiles while maintaining the load within some target level; this allocation would be dynamic, and change when new connections arrive or when old ones terminate.

5 Numerical Investigations

In this section we present numerical investigations demonstrating the model proposed in the previous sections. The discussion of the results from these investigations allow us to reach some qualitative conclusions on how a user's valuation for his average throughput and the percentage of time slots he can transmit in, should affect his optimal selection of these parameters.

We consider the case where users have a utility function that is the sum of the two factors given by (21) and (22). Figure 3 shows the throughput factor for the two values of parameter u_i in (21) that we consider; observe that a larger value of u_i results in a higher valuation for the same transmission rate, or equivalently the same valuation for a smaller rate. Figure 4 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 (22) that we consider; observe that a larger value of v_i results in a higher valuation for the same percentage of time slots, or equivalently the same valuation for a smaller number of time slots.

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 [11]

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

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 that we consider in the numerical investigations of this section are shown in Table 1.

Figure 5 shows the tradeoff between the transmission rate r and the percentage of time slots ϕ a user is allowed to transmit; this tradeoff is computed from (14), 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 ϕ a user should be allowed to send is close to one. Next we explain both of these behaviours.

The former behaviour, i.e. the percentage of time slots is close to one for small values of the transmission rate is due to the following: For small values of the transmission rate, the right-hand side of (13) obtains small values, hence the derivative V_i' should be small, which is the case for large values of ϕ due to the concavity of V_i , Figure 4. Intuitively, this regime corresponds to the case of a heavily loaded system, where each user is allocated a small percentage of the total resource. Hence, the amount of resource usage for each user i is

$$\alpha_i = \frac{r_i \gamma_i}{W + r_i \gamma_i} \approx \frac{r_i \gamma_i}{W},$$

i.e. the resource usage of each user becomes approximately proportional to his average throughput. In this case, for the same average throughput and hence the same amount of resource usage, the utility of a user is higher for a higher percentage of time slots, since the factor $V_i(\phi_i)$ in (22) is an increasing function

of the percentage of time slots ϕ_i . Hence, in this case users should choose large values for ϕ_i .

The latter behaviour, i.e. the percentage of time slots is close to one for large values of the transmission rate can be explained as follows: Large values of the transmission rate will be realized in a lightly loaded system, in which case the shadow price λ obtains a small value. Hence, from (13), the derivative V_i' should be small, which is the case for large values of ϕ .

From the comparison of the different graphs in Figure 5 we can make the following conclusions regarding the effects of the user utility factors. First, a larger value of u , which corresponds to higher valuation for the average throughput, Figure 3, results in the optimal transmission rates obtaining smaller values. Second, a higher value of v , which corresponds to higher valuation of the percentage of slots a user can transmit in, Figure 3, results in the optimal percentage of time slots obtaining smaller values.

Figure 6 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 4, a network provider would determine the optimal transmission rate, based on the number and type of users, from Figure 6, and then the optimal percentage of time slots a user is allowed to transmit, from Figure 5.

6 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 and application QoS 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. Furthermore, our numerical investigations enable us to make some qualitative observations on how a user's valuation for his average throughput and the percentage of time slots he can transmit in, should affect his optimal selection of these parameters. 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 extending the model to the case where users value, in addition to the average throughput, the packet loss probability; work related to this is presented in [12]. Finally, a more practical issue involves identifying specific forms of utility functions that correspond to the QoS requirements of actual applications.

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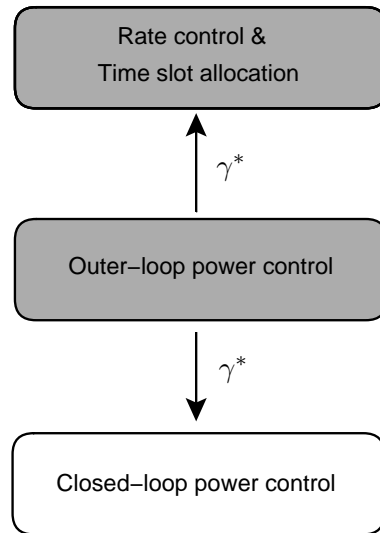


Figure 1: Only the rate and time slot control, and the outer-loop control procedures (shaded boxes) are affected by the proposed resource control model; on the other hand, closed-loop power control remains unaffected. The target signal quality is provided as input to both the rate control and time slot allocation procedures, and to the closed-loop power control procedure.

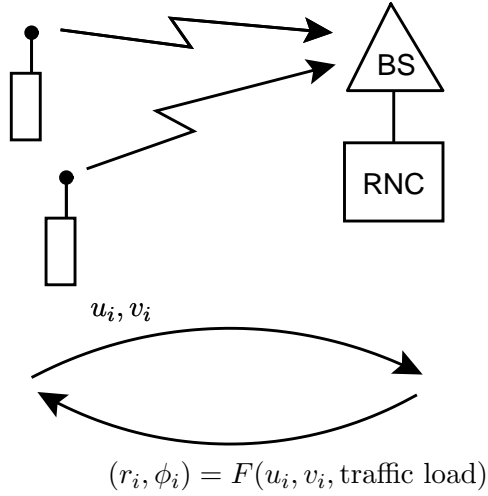


Figure 2: Class-based implementation of the proposed model. Each user selects a class corresponding to particular values for u_i, v_i . Based on this selection, and taking into account the network load, the RNC computes the optimal transmission rate and percentage of time slots the user can transmit.

Table 1: Parameters used in the numerical investigations.

parameter	value
chip rate, W	3.84 Mcps
load, ρ	60%
$BER(\gamma)$ (DPSK)	$0.5e^{-\gamma}$
bits per pkt, L	60
γ^* , from (12)	5 (= 7 dB)
throughput factor	$U(x) = 1 - e^{-ux}$, $u = 0.1, 0.2$
time slot factor	$V(\phi) = 1 - e^{-u\phi}$, $v = 10, 20$

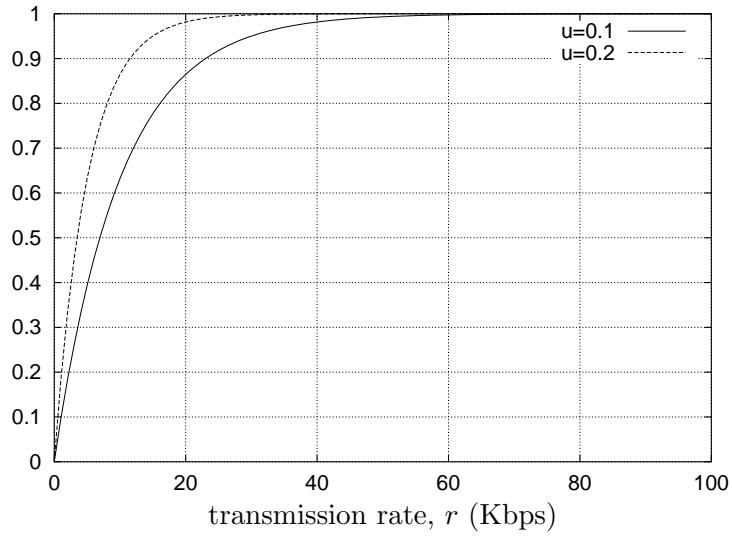


Figure 3: Throughput utility factor given by (21), for $u = 0.1, 0.2$.

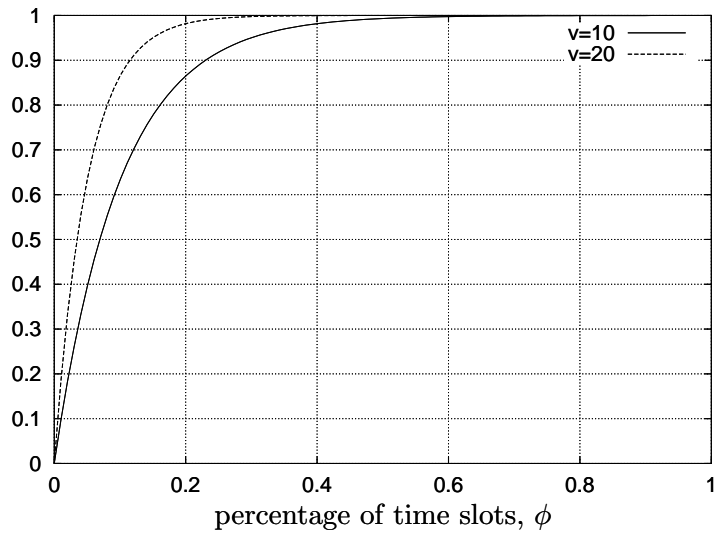


Figure 4: Utility factor related to the percentage of time slots given by (21), for $v = 10, 20$.

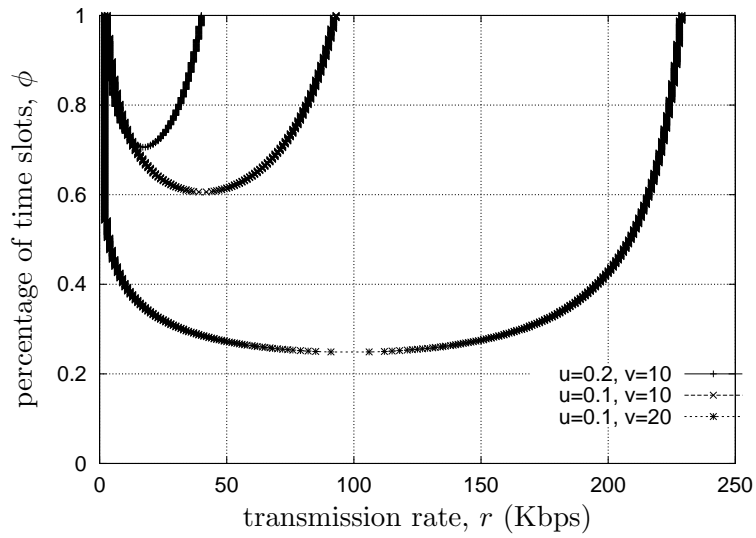


Figure 5: Tradeoff between transmission rate and percentage of time slots a user can transmit.

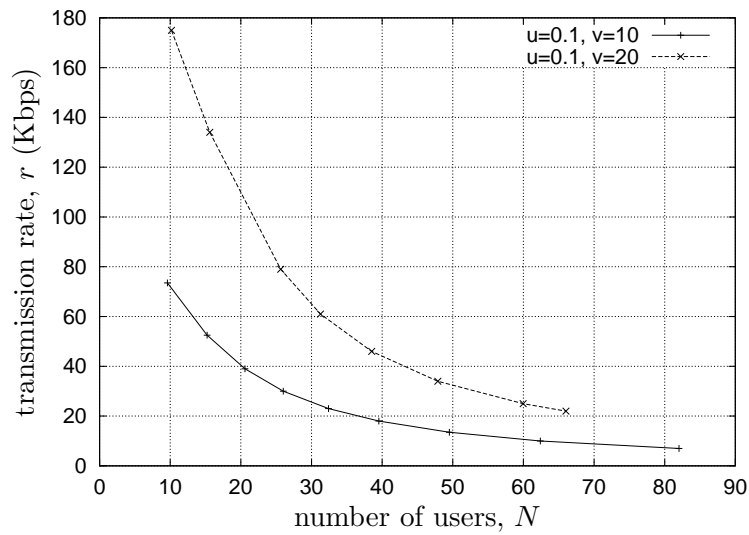


Figure 6: Optimal transmission rate for a different number of users.