

# A cross-layer cost-function based rate adaptation mechanism for the WCDMA system with multi-class services by transport format selection

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## Summary

The growing demand of high speed multi-class data transmissions poses new challenges on wireless networks. The major objectives of the next generation wireless networks include: (1) achieving high data throughput in the fast varying wireless channel; (2) transmitting multi-class data by service multiplexing; and (3) controlling the delay for delay sensitive service. To achieve these goals, in the context of wideband code division multiple access (WCDMA) system, we propose a cost-function based rate adaptation mechanism by taking account of both physical layer channel impacts and higher layer performance parameters, such as buffer occupancy and service priority. We implement this cross-layer rate mechanism by exploiting the transport format (TF) selection procedure in the medium access control (MAC) layer of the WCDMA system. Through the proposed cross-layer cost function, the TF selection procedure can dynamically adapt suitable spreading factors every transmission time interval (TTI), usually 10–80 ms. Through simulations in a flat Rayleigh fading channel, we show that the proposed cross-layer cost-function based rate adaptation mechanism can effectively improve throughput and reduce the buffer occupancy for multi-class services for the WCDMA system at the cost of slightly higher power efficiency. Copyright © 2005 John Wiley & Sons, Ltd.

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**KEY WORDS:** rate adaptation; transport format selection; the WCDMA system; cross-layer design

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## 1. Introduction

Delivering multi-class services in a fast varying radio channel is an important application as well as a big challenge for the next generation wireless network. In the future, wireless applications are foreseen to contain various types of services with digital camera with different quality of service (QoS) requirements. One good example is the smart handsets with digital

camera. Therefore, how to improve transmission efficiency in supporting multi-class services becomes an important issue for the future mobile cellular system.

Basically, challenges for supporting multi-class services in the wireless systems are mainly threefolds: (1) transmitting high-speed data in a time varying fading channel; (2) sharing radio resource among multi-class services fairly; and (3) controlling the delay for each type of services. First, rate adaptation

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techniques adapt transmission parameters with respect to fast-varying channel conditions in order to fully utilize channel capacity. If it is in a favorable channel condition, the transmitter can apply a smaller value of spreading factor to increase data rates. On the contrary, a larger spreading factor is used in a poor channel condition. Second, in addition to rate adaptation mechanisms, it is still necessary to incorporate other radio resource allocation schemes in the higher protocol layer to effectively support the multi-class services in radio environments. Usually, multi-class services are served based on predefined priorities. However, a strict priority based allocation algorithm may cause a long service delay for a low-priority service [1]. Thus, minimizing buffer occupancy for each service is also an important factor in the design of resource allocation algorithm for multi-class services.

In the WCDMA system, the transport format (TF) selection procedure plays a key role in supporting multi-class services. The transport format is accompanied with each transport channel, which determines the transmission rate and other physical layer parameters [2,3]. The purpose of the TF selection procedure is to provide multi-class services through selecting a suitable TF according to a user's traffic load and service type. In the literature, some TF selection procedures have been proposed from different perspectives [1,4,5]. The TF selection algorithms in References [1,4] are mainly from the viewpoint of the user's traffic requirement, whereas the one in Reference [5] is from the physical layer perspective. In Reference [4], with respect to single type service, the credit-based and the maximum rate based TF selection procedures were proposed to reduce the buffer occupancy. In Reference [1], with consideration of different priority and buffer occupancy conditions, the authors proposed and compared different TF selection algorithms in selecting multiple transport channels for supporting multi-type services. In Reference [5], the authors proposed a TF selection procedure with a sophisticated power distribution process among multiple users under the AWGN channel.

The objective of this paper is to design a TF selection based rate adaptation mechanism from the MAC and physical cross-layer perspectives. To this end, we first introduce a multi-state rate adaptation scheme to capture the Rayleigh fading channel variations and then apply this scheme to the TF selection procedure in the medium access control (MAC) layer. We utilize a cost function to incorporate service priority and buffer occupancy of the MAC layer and

radio link quality of the physical layer. Jointly adopting the cross-layer cost-function and the multi-state rate adaptation mechanism, the TF selection procedure can further enhance data throughput and the fairness guarantee when supporting various types of traffic.

The rest of this paper is organized as follows. In Section 2, we present our proposed multi-state rate adaptation scheme. In Section 3, we discuss how to implement rate adaptation schemes by applying the TF selection procedures of the wideband code division multiple access (WCDMA) system. Section 4 shows the simulation results. Section 5 gives our concluding remarks.

## 2. Multi-State Rate Adaptation Algorithm

### 2.1. Motivation

We first explain the motivation of developing a new rate adaptation algorithms from the physical layer perspective. The effects of path loss, shadowing, multi-path fading, and mobility result in a complicated time-varying wireless channel. One of the popular channel models used for the scheduling algorithm is the two-state Markov model [6]. Figure 1 shows an example of a wireless fading channel and its corresponding two-state Markov channel model. The basic idea of rate adaptation schemes based on the two-state Markov model is described as follows. As shown in Figure 1, when the channel is in the bad state, for example, during  $[t_1, t_2]$ , the system stops transmitting any data. As the channel condition becomes better, such as in  $[t_2, t_3]$ , the backlogged traffic flow can be compensated by allowing to use more channel resource.

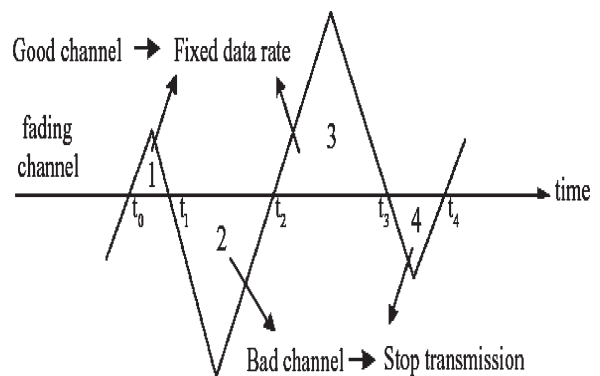


Fig. 1. Two-state rate adaptation model.

The drawback of using the two-state on-off model for rate adaptation is the limited number of channel states, which may degrade the efficiency in utilizing radio resource. Take Figure 1 as an example. Because of the bad channel condition during  $[t_3, t_4]$ , the scheduler will ask a user to stop transmission. In fact, the channel condition in  $[t_3, t_4]$  may not be so bad, which can still support a lower data rate. On the other hand, in a good channel condition such as in  $[t_2, t_3]$ , we can transmit at a higher data rate than in  $[t_0, t_1]$ . Obviously rate adaptation based on the two-state on-off channel model cannot fully utilize channel capacity. This observation motivates us to develop a multi-state rate adaptation technique, which is described in the next subsection.

### 2.2. Rate Adaptation Procedures

Instead of using the two-state on-off channel model, we propose a multi-state rate adaptation (MSRA) scheme to adapt the transmission parameters to follow the channel variations. The basic idea of the MSRA scheme is to adjust the spreading factor dynamically through changing TF in the WCDMA system. The proposed algorithm can be used in a channel such as the random access channel (RACH) in which only open loop power control is applied.

We now illustrate the key procedures of the MSRA mechanism. The first step is to partition the cumulative distribution function (CDF) of the received signal to noise ratio (SNR) into multiple regions. Then, we map each region to different data rates in the rate adaptation algorithm. In this paper, different transmission rates can be achieved by adjusting spreading factor. In the CDMA system, the relation between spreading factor and the received energy bit to noise density ratio (denoted as  $E_b/N_0$ ) can be written as

$$\frac{E_b}{N_0} = \frac{S}{N} \frac{W}{R_b} \tag{1}$$

where  $S/N$  is the signal to noise ratio,  $W$  is the bandwidth, and  $R_b$  is the data rate. Denote the processing gain (PG) as

$$PG_{dB} = 10\log\left(\frac{W}{R_b}\right) \tag{2}$$

Then, from Equation (1) and (2), we have

$$PG_{dB} = \underbrace{SNR_{dB}}_{\text{received signal quality}} - \underbrace{\left(\frac{E_b}{N_0}\right)_{dB}}_{\text{required signal quality}} \tag{3}$$

Equation (3) implies that a suitable processing gain (or spreading factor) can be determined for the required  $E_b/N_0$  according to the received SNR statistics. Figure 2 shows a CDF of the received SNR with multiple rate adaptation regions.

One of the keys to implement this multi-state rate adaptation scheme is to determine a set of multiple SNR thresholds for rate transitions. We suggest the following procedures to decide these SNR thresholds in Figure 3:

- (1) Determine the required block error rate (BLER). In the WCDMA system, the BLER performance is usually required to be smaller than 10% for providing non-delay-sensitive services in a mobile terminal [7,8].
- (2) Calculate the corresponding  $(E_b/N_0)_{dB}$  for the required BLER based on an off-line simulation in the Rayleigh fading channel.
- (3) Calculate the required SNR thresholds (denoted as  $\eta_i$ ) for different spreading factors based on the following condition:

$$\eta_i = (E_b/N_0)_{required,dB} - 10\log SF_i \tag{4}$$

where  $SF_i = 2^i$  ( $i = 1$  to  $N$ ), and  $N$  is the number of available spreading factor.

By putting these thresholds into the CDF curve, we can define the spreading factor in the rate adaptation scheme as the state variable. The average throughput  $\bar{Th}$  can be determined as follows:

$$\bar{Th} = \sum_i \pi_i \times Th_i \tag{5}$$

where  $\pi_i$  is the steady state probability in the multi-state Markov chain and  $Th_i$  denotes the achievable

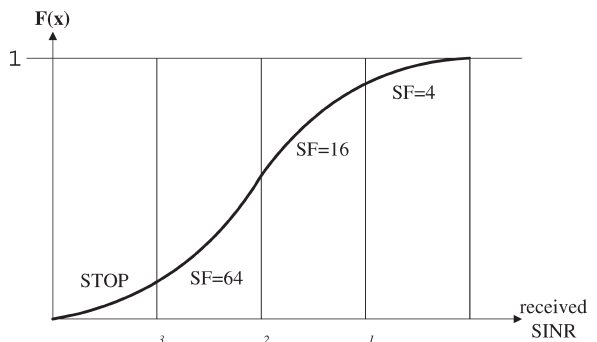


Fig. 2. An example of the cumulative distribution function (CDF) of the received signal to noise ratio (SNR).

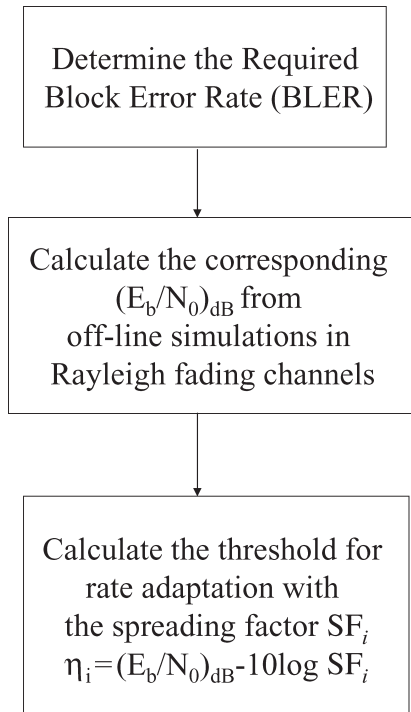


Fig. 3. Procedure to determine the function.

throughput in state  $i$ . In Section 4, Equation (5) is used to verify the system throughput by simulation.

### 2.3. State Transition Schemes

In this paper, we consider two compensation schemes for rate adaptation: (i) incremental compensation and (ii) direct compensation.

#### 2.3.1. Rate adaptation with incremental compensation

Based on the incremental compensation principle, the next state for rate adaptation is limited to one of the two neighboring states or the current state itself. Figure 4 shows an example of rate adaptation with incremental compensation. For example, if the system is in state 'SF = 16' and the SNR measurement is lower than  $\eta_3$ , then the next state will be 'SF = 64'

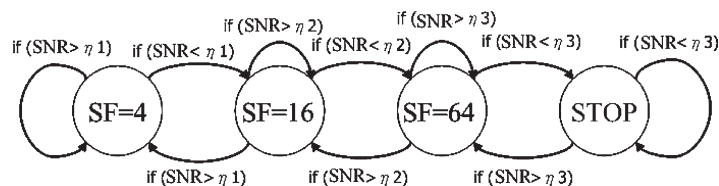


Fig. 4. Multi-state rate adaptation model with incremental compensation.

instead of 'STOP.' On the other hand, if in state 'SF = 16,' the received SNR is higher than  $\eta_1$ , then the next state will be 'SF = 4.'

#### 2.3.2. Rate adaptation with direct compensation

The next state for rate adaptation based on direct compensation can be any state in the state space, as shown in Figure 5. Direct compensation can change data rates much faster than the incremental compensation scheme.

#### 2.3.3. Assumptions

For the multiple users case, we assume that the open loop power control has compensated the path loss and shadowing effect for each individual user. When doing the multi-state rate adaptation mechanism, we calculate the received signal to interference plus noise ratio (SINR) to decide the selected data rate for the next time instant. The numerical results with multiple users will be discussed later in Section 4.

## 3. Cost-Function Based Transport Format Selection

### 3.1. Background and Motivation

In the WCDMA system, data rates can be adapted by changing spreading factors through selecting different TF. Defining appropriate transport formats is the responsibility of the MAC layer scheduling algorithm. Specifically, a MAC layer scheduling algorithm schedules logical channels according to service priorities and buffer occupancies (BO) in the upper radio link control layer [1,10]. With the TF information, the transport channel in the physical layer knows how many data bits are waiting in the MAC layer and will manage to transmit the data to the physical layer. From the observation in Section 2, the radio link quality in the physical layer should also be taken into account of the TF selection procedure. Thus, we are motivated to develop a cross-layer cost function to incorporate the radio link quality of the physical layer

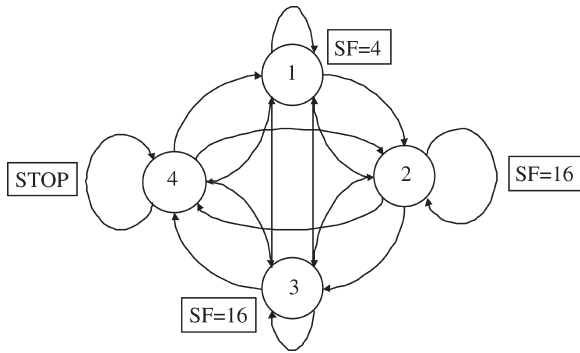


Fig. 5. Multi-state rate adaptation model with direct compensation.

and service priorities and buffer occupancies of the MAC layer.

The key to the cross-layer cost-function based TF selection procedures is to find a suitable indicator in the MAC layer that can represent the radio link quality in the physical layer. First, we give some background on the transport format. The transport format includes dynamic part and semi-static part. The dynamic part of a transport format contains the information of transport block (TB) and transport block set (TBS). The size of TBS defines the number of bits to be sent during a transmission time interval (TTI), while the size of TB defines the basic unit exchanged between the physical layer and the MAC layer. We denote  $|TBS|/|TB|$  as the number of transport blocks within a TTI waiting for transmission. The semi-static part of a transport format includes transmission time interval, error protection scheme, coding rate, static rate matching parameter, and the size of cyclic redundancy check (CRC). The semi-static part of information does not change very often. Table I shows an example of transport format set in Reference [9]. By selecting different sizes of the transport block set, we can obtain different spreading factors. For example, when the size of transport block set is increased from 320 to

5760, the spreading factor is reduced from 64 to 4 in the considered case.

Second, we suggest adopting  $|TBS|/|TB|$  as the indicator of the link quality:

$$\gamma_k = g(|TBS|/|TB|) \tag{6}$$

where  $\gamma_k$  is the SNR in the  $k$ th TTI, and  $|TBS|/|TB|$  is the number of transport blocks that will be transmitted in the next TTI for this indicator. We explain why Equation (6) can represent the radio link quality as follows. Recall that  $|TBS|/|TB|$  is determined in the multi-state rate adaptation scheme. Note that a larger value of  $|TBS|/|TB|$  leads to a higher rate of data transmissions, which requires a smaller spreading factor. Hence, a larger  $|TBS|/|TB|$  can represent a better link quality in the physical layer.

### 3.2. Proposed Cost-Function Based TF Selection Procedure

In order to utilize radio resource efficiently and meet the QoS requirements, we propose a cost-function based transport format selector with consideration of the following three parameters: (1) BO, (2) service priority, and (3) radio link quality. The BO represents the number of blocks in the buffer of radio link control (RLC) layer [10]. Service priority distinguishes services of different delay requirements with different priorities.

In order to choose a suitable cost function, we have the following general guidelines:

- (1) The service with higher priority needs to get more channel capacity to reduce the transmission latency. That is, if type  $i$  service has a higher priority than type  $j$  service, then  $(|TBS|/|TB|)_i > (|TBS|/|TB|)_j$ .

Table I. Transport format sets used in the simulation.

Parameter	SF = 64	SF = 32	SF = 16	SF = 8	SF = 4
Information Bit rate [kbps]	16	32	64	128	384
DPDCH (physical rate) [kbps]	60	120	240	480	960
Transport block size (bits)	320	320	320	320	320
Transport block set size (bits)	320	640	1280	2560	5760
Transmission time interval (ms)	20	20	20	20	20
Transport blocks per TTI	1	2	4	8	18
Types of error protection	Conv. Coding	Conv. coding	Conv. coding	Conv. coding	Conv. coding
Coding rate	1/3	1/3	1/3	1/3	1/3
Rate matching attribute	256	256	256	256	256
Size of CRC	16	16	16	16	16

- (2) Denote  $BO_i$  the number of blocks queued in the buffer for the next TTI. The more the resource obtained the lower the value of  $(BO_i - (|TBS|/|TB|)_i)$ . When  $BO_i$  is smaller than  $(|TBS|/|TB|)_i$ , it is implied that current allocation wastes too much capacity for this service. In order to prevent such a situation, we include  $(BO_i - (|TBS|/|TB|)_i)^2$  in the cost function.
- (3) If the service with higher priority occupies all channel capacity, the total cost of other services with lower priority may also become very large. Thus, we need to sum the product of the priority parameter and  $(BO_i - (|TBS|/|TB|)_i)^2$  of all services into the cost function.

Through, the cross-layer design between the physical layer and the MAC layer, the above characteristics motivate us to define a cost for TF selection as follows:

$$\text{Cost} = \left( \sum_{i=1}^S \left( \text{pri}_i^\alpha (BO_i - (|TBS|/|TB|)_i)^2 \right) \right) \quad (7)$$

where  $S$  is the total number of services for a user and  $\text{pri}_i$  is the priority of type  $i$  service. Note that the parameter  $\alpha$  in Equation (7) is chosen to make the contribution of service priority  $\text{pri}_i^\alpha$  on the cost function be equal to that of  $(BO_i - (|TBS|/|TB|)_i)^2$ . In our case, we choose  $\alpha = 4$  through some experiments. Based on Equation (7), the TF selector can calculate all the combinations of possible transport block sets for multiple services. Then the objective of the TF selection procedure is to choose the best transport block combination to minimize the cost function, that is

$$\text{Objective : } \min_{\{|TBS|/|TB|_i\}, i \in S} \text{Cost} \quad (8)$$

Table II. The cost of every possible transport block set combinations.

Possible transport block set combination	Type 1 service	Type 2 service	Cost
1	2	1	2500
2	2	0	5625
3	1	2	10625
4	1	1	12500
5	1	0	15625
6	0	3	42500
7	0	2	40625
8	0	1	40000
9	0	0	45625

For example, consider a situation when the total available resource in the next TTI is three transport blocks, while two type 1 data blocks and three type 2 data blocks are queued in the buffer with priority of 10 and 5, respectively. Table II lists all the possible combinations of transport block sets and their corresponding costs according to Equation (7). From the table, combination 1 has the minimum cost. Hence, the cost-function based TF selector will choose two transport blocks for type 1 service and one transport block for type 2 service.

### 3.3. Implementation

Figure 6 shows the block diagram of the TF selector in the MAC layer and its relation to the radio resource management (RRM) layer and radio resource control (RRC) layer. When the connection is established, the radio resource management controller (RRMC) will

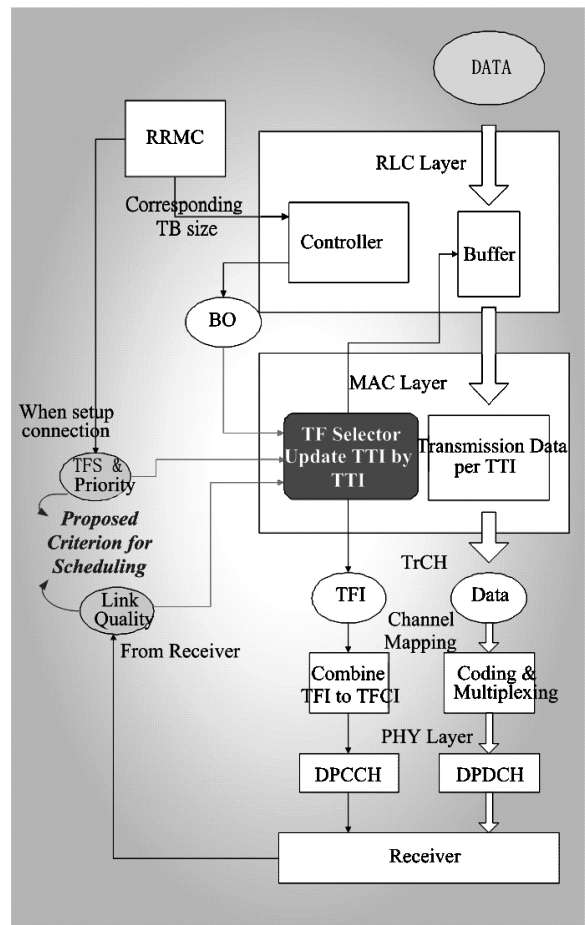


Fig. 6. System block diagram of transport format (TF) selection.

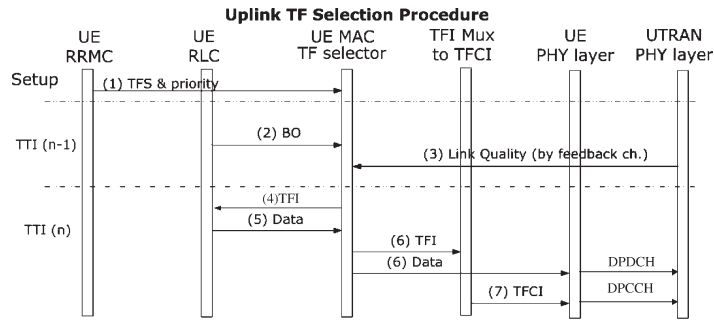


Fig. 7. TF selection procedures blocks according to the transport format information.

assign a group of transport formats according to different service types. Each connection can have different service priorities. When data are processed in the RLC layer, the RLC controller divides data in the buffer into multiple blocks according to the transport format information. Figure 7 shows the TF selection procedures with consideration of three aforementioned input parameters, that is BO, priority, and  $|TBS|/|TB|$ . As shown in Figure 6, instead of calculating the cost function at a base station, we design each user to distributively determine the best transport block set combination according to the proposed cost function in Equation (7). Thus, the complexity of calculating the minimum cost can be reduced significantly. In a typical case, when a user has two services to be transmitted and the available transport blocks for the next TTI is equal to  $B$ , all the possibilities in the calculation of the cost function is less than  $(B + 2) \times (B + 1)/2$ . In Table II, for instance, the number of computations is less than 10.

#### 4. Simulation Results

We perform simulations under a Rayleigh fading channel to evaluate the proposed cost-function based multi-state rate adaptation mechanism. We will first examine the performance of different rate adaptation schemes in terms of throughput and power efficiency. Then, we apply the proposed cost-function based TF selection procedure to examine the buffer occupancy performance when transmitting multiple services.

Figure 8 shows an example of the received SNR in a Rayleigh fading channel with Doppler frequency equal to 5.5 Hz. The top plot in Figure 8 is the actual SNR per time slot, and the bottom one is the measured average SNR in every TTI (i.e., 20 ms in this example).

According to the received SNR of the channel described in Figure 8, the numbers of successfully

transmitted data blocks in every TTI for the two-state and multi-state rate adaptation schemes are shown in Figure 9. In the figure, plot (a) is the case without rate adaptation, (b) the case of the two-state rate adaptation, (c) the case of using multi-state rate adaptation with incremental compensation, and (d) the case with direct compensation. In the figure, one can find that compared to the case without rate adaptation, the multi-state rate adaptation can avoid unnecessary transmissions in a bad condition. Furthermore, the throughput with multi-state rate adaptation is better than that without rate adaptation. However, the system with the two-state rate adaptation improves the power efficiency at the expense of lower throughput. Power efficiency is defined as the number of TTIs with transmitted data blocks over the total number of TTIs. Table III compares the throughput and power consumption for the two-state and multi-state rate adaptation schemes normalized to the case without using rate adaptation. Here the throughput gain is defined as

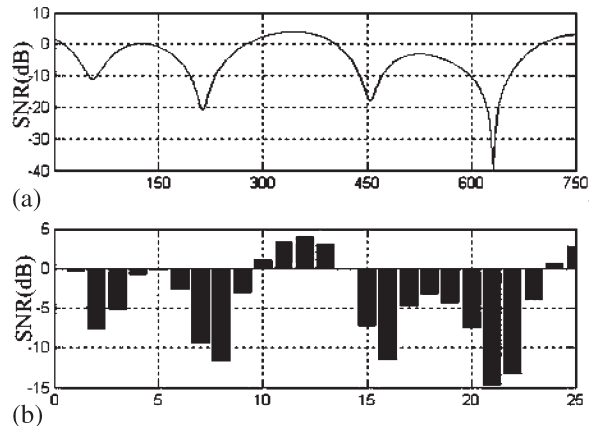


Fig. 8. An example of received SNR in a Rayleigh fading channel with Doppler frequency equal to 5.5 Hz: (a) mean SNR per slot, slot unit 0.667 ms; (b) mean SNR per TTI, TTI unit 20 ms.

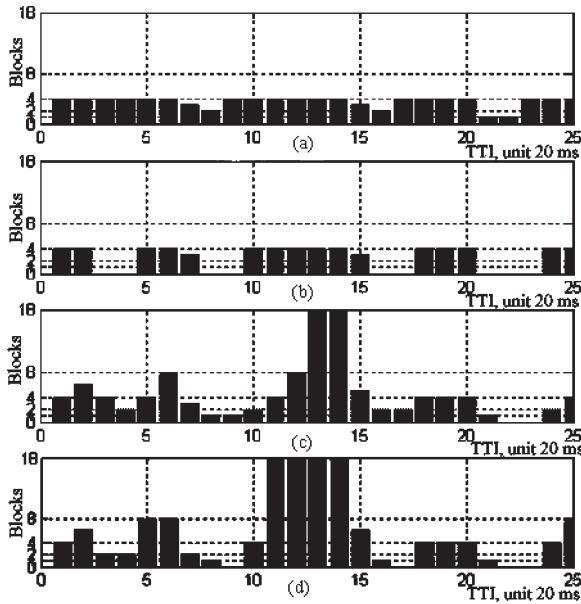


Fig. 9. Throughput comparison for different rate adaptation schemes, where (a) without rate adaptation, (b) two-state rate adaptation, (c) multi-state rate adaptation with incremental compensation, and (d) multi-state rate adaptation with direct compensation.

$$\overline{\text{Th}}_{\text{gain}} = \frac{\overline{\text{Th}}_{\text{rate adaptation}}}{\overline{\text{Th}}_{\text{without rate adaptation}}} \quad (9)$$

As shown in the table, the multi-state rate adaptation with incremental compensation improves throughput by 280% compared to the two-state rate adaptation scheme at the expense of slightly higher power consumption. With direct compensation, the throughput of multi-state rate adaptation increases to 300% compared to the two-state rate adaptation scheme. Table IV shows the average throughput obtained by analysis and simulation. We find that the throughput obtained from simulation is close to the analytical results obtained from Equation (5).

Table III. Throughput gain and power consumption comparison (note that the case without rate adaptation is the reference case.)

	Power consumption	Throughput gain
Multi-state rate adaptation with incremental compensation	99.6%	234.06%
Multi-state rate adaptation with direct compensation	94.8%	258.07%
Two-state rate adaptation	82.0%	83.85%

Table IV. Throughput comparison for the multi-state rate adaptation with direct compensation by analysis and simulation.

	Analytical value	Measurement base
Average throughput (blocks/TTI)	10.0278	9.828

Table V. Throughput gain and BLER performance comparison for different users in the system.

	2 users	3 users	4 users	5 users	8 users
Average throughput gain	232.00%	201.86%	191.08%	179.21%	161.58%
Average BLER	3.12%	4.04%	3.7%	4.21%	4.77%

Table V shows the performance of multiple users on the proposed multi-state rate adaptation schemes. Due to the existence of the interference, as the number of users increases, the throughput gain of the proposed multi-state rate adaptation scheme decreases because of the mutual interference among users. From the table, we note that the block error rate (BLER) is still maintained below 10%. It is implied that the rate adaptation mechanism can still work in the multiple user environment.

Figure 10 shows the effect of transmitting an image file using the TF selection with the multi-state rate adaptation and that without using the TF selection. Figure 10(a) is the original picture, while Figure 10(b),(c) are the results with and without using the proposed rate adaptation scheme. One can see that for the picture with TF selection (Figure 10(b)), rate adaptation can reduce retransmissions. However, without using the TF selection (from Figure 10(c)), a lot of blocks are lost due to radio channel impairments.

Figure 11 compares the performance of the multi-state rate adaptation with that of the method using the fixed transport format. An ARQ retransmission

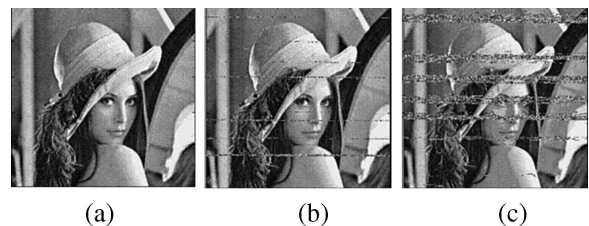


Fig. 10. Effect of multi-state rate adaptation on transmission of an image file, where (a) original bit-map picture, (b) with using TF selector, and (c) without TF selector.



mechanism is considered in this example. One can observe that compared to the case of using a fixed four transport blocks per TTI, the multi-state rate adaptation scheme can reduce transmission time from 4800 TTIs to 2800 TTIs, while maintaining almost the same retransmission ratio. Here the retransmission ratio is defined as the average retransmission time for corrupt data blocks over the total transmission time. As shown in Figure 11, when the number of transport blocks per TTI is equal to 18 (i.e., the spreading factor is equal to 4 referring to Table I), the transmission time is shortest, but with many errors. On the other hand, when the number of transport blocks is two per TTI (i.e., spreading factor is equal to 32), error blocks are reduced but requires much longer transmission time.

Figure 12 illustrates the performance according to our proposed cost-function based multi-state rate adaptation scheme for multi-type services. For comparison, Figure 13 shows the number of blocks queued in the buffer according to the traditional strictly priority based TF selection [1]. We assume that a user transmits two types of services with different priorities. Table VI lists the related parameters. In this example, we assume type 1 service has higher priority than type 2 service. By comparing Figures 12 and 13, we know that for type 1 service, the queue length and

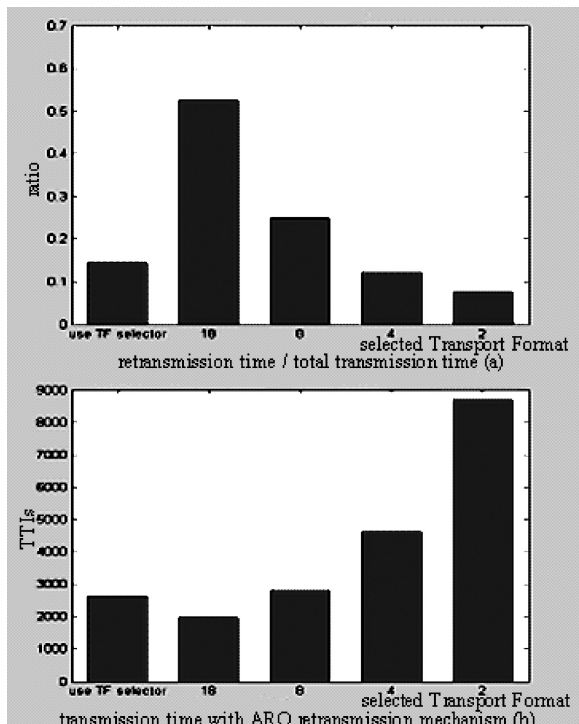


Fig. 11. (a) Retransmission ratio and (b) total transmission time (msec) with different number of blocks per TTI.

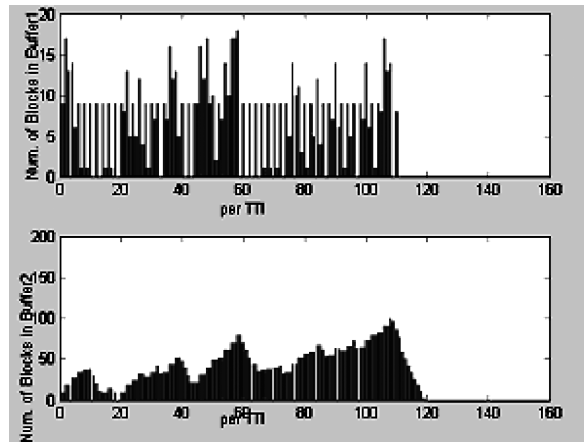


Fig. 12. Buffer occupancy with proposed cost-function based MAC Scheduler, where service in buffer 1 has higher priority than in buffer 2.

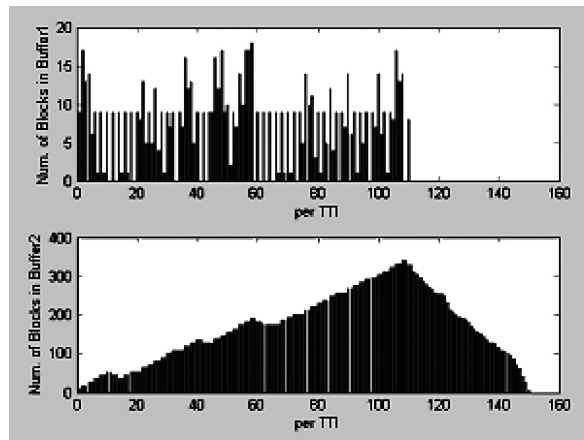


Fig. 13. Buffer occupancy for each service with conventional strict priority based scheduler, where service in buffer 1 has higher priority than in buffer 2.

service time are similar for both methods. For type 2 service, the proposed cost-function based TF selector needs a smaller buffer and shorter service time compared to the strictly priority based TF selector. Specifically, for type 2 service, the cost-function based TF

Table VI. Simulation parameters for the multi-type services.

	Service 1	Service 2
Service type	Higher priority data	Lower priority data
Service priority	10	5
Data rate	72 kbps	72 kbps
Transport block size	320 bits	320 bits
Data amount	282 blocks	282 blocks
Arrival rate	9 blocks	9 blocks
(from high layer)	per 2 TTI (40 ms)	per 2 TTI (40 ms)

selector can reduce the total transmission time from 150 to 120 TTIs compared to the strictly priority based TF selection. Recall that our cost function takes into account both service priority, buffer occupancy, and link quality (see Equation (6)). Thus, our cost function will assign more transport blocks to the service with higher priority in order to reduce the cost. Furthermore, if its buffer size is too large, the service with lower priority will also increase the cost. In this case, our algorithm with the goal of minimizing the cost can assign transport blocks to the service with lower priority. Consequently, the proposed cost-function based multi-state rate adaptation can utilize the available transport blocks more effectively and achieve fairness among different services simultaneously.

## 5. Conclusion

In this paper, we have proposed a new cost-function-based transport format selection mechanism for the WCDMA system. We implement the proposed multi-state rate adaptation technique in the context of the transport format selection procedures of the WCDMA system. The proposed transport format selection mechanism, based on the multi-state channel model, performs better than the scheduling algorithm based on the two-state on-off channel model. Moreover, we proposed a new cross-layer cost function between the

MAC layer and the physical layer to incorporate many important factors such as service priority, buffer occupancy, and radio link quality. Our results demonstrate that the proposed cost-function-based MAC scheduling combined with physical layer multi-state rate adaptation can effectively enhance throughput, save power, and guarantee service fairness in wireless data networks.

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