行政院國家科學委員會補助專題研究計畫成果報告

自主整合式WCDMA基地台街收系統之MAC協定之改進與實現

計畫類別：□個別型計畫　　■整合型計畫
計畫編號：NSC 90－2219－E－009－012
執行期間：　　90 年 8 月 1 日 至　91 年 7 月 31 日

計畫主持人：王蒞君副教授

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- □國際合作研究計畫國外研究報告書一份

執行單位：交通大學電信工程系

中　華　民　國　91　年　8　月 10　日

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自主整合式 WCDMA 基地台街收系統之 MAC 協定之改進與實現

Joint Physical Layer Multi-State Rate Adaptation and MAC Scheduling for WCDMA Systems by Transport Format Selection[1]

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中文摘要

在 WCDMA 中，多樣化的服務為其重要特性。目前能達到此目標的方法並不完備。此研究成果是針對 Transport Format Selection 來發展排程技術去適應多變的通道特性，以達到高效率、高品質的無線寬頻環境。

本計畫之特點：第一，結合實體層及媒體存取控制層的資訊，來做 Transport Format 之選擇的最佳化設計。第二，兼顧同一使用者，多種服務之間的動態調整。第三，採用目前 3GPP 中之 TF Selection 來做排程技術及速率調整之準則，是能夠實現的。

在 Transport Format 的選擇方面，我們考慮了三個參數。

（**a**）Priority：代表的是不同 service 之間的前後優先次序。

（**b**）Buffer Occupancy：代表的是無線連線控制層(RLC)的暫存器內，仍有多少資等待傳送。

（**c**）Link Quality：代表的是由實體層估測到的下一個傳送時間間格(TTI)的通道可能變化情形。

經由這三個參數，提供給媒體存取控制層(MAC)中 Transport Format 選擇的重要依據。藉此達到無線資源在連線層(Link Layer)和媒體存取控制層(MAC)的交互最佳化。

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[1] 本文已經 submitted to IEEE ICC 2003 ，詳細內容如附件。

Joint Physical Layer Multi-State Rate Adaptation and MAC Scheduling for WCDMA Systems by Transport Format Selection

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Abstract-

This paper presents a multi-state channel model for rate adaptation and MAC scheduling in the WCDMA system. According to the cumulative density function of the received SINR in the physical layer, a set of thresholds are determined to change spreading factors via the Transport Format (TF) selection procedures in the MAC layer. Moreover, we proposed a new cost function based TF selection procedure to incorporate all the important factors, such as service priority, buffer occupancy, and the number of data blocks to be sent. This new TF selection algorithm in the MAC layer combined with the multi-state rate adaptation scheme in physical layer can achieve the ultimate goals of the wireless scheduling simultaneously: (1) throughput enhancement; (2) power saving; and (3) service fairness guarantee.

Keywords: **Rate Adaptation, Channel Variation, Transport Format Selection**

Ⅰ. INTRODUCTION

SCHEDULING is a very important technique for resource management in both wireline and wireless networks. In wireless networks, many scheduling techniques, such as weighted fair queuing [1], packetized general processor sharing [2], have been proposed to provide fair channel access among many contending hosts. However, to apply these wireline scheduling algorithms to wireless networks is nontrivial because wireless networks present many challenges in both channel environments and system requirements.

The key challenges in designing wireless scheduling algorithms are aimed not only to achieve the goal of fairness as in wireline networks, but also to enhance throughput and save the user terminal's power consumption in a time-varying wireless channel. In a typical wireless channel, the effects of path loss, shadowing, multi-path fading, and user mobility will lead to channel variations, thereby causing performance degradation if using the traditional wireline scheduling algorithms. For example, for a user scheduled to transmit in bad channel condition, the user's data will be lost most likely. Furthermore, the wasted transmission power will shorten the battery life of user terminals. Consequently, one of the most important factors in designing wireless scheduling algorithm is to take into account of channel variation of wireless systems.

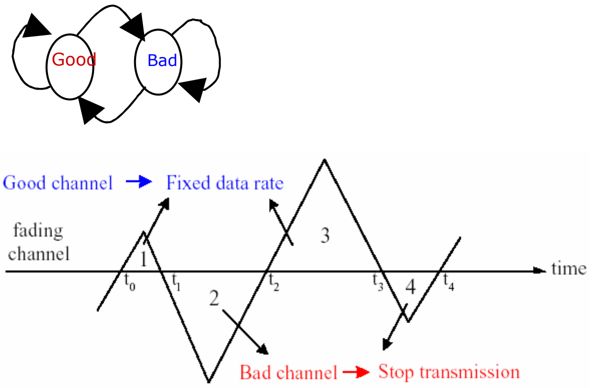

Fig. 1. Two-State Rate Adaptation Model.

Specifically, the goal of wireless scheduling is to make channel variations transparent to users dynamically allocating radio resource according to channel conditions. One of the most popular models used in current wireless scheduling algorithms is the two-state Markov channel model [3]. The two-state Markov model defines the channel as *good* (or *error-free*) state if the channel gain is above a predetermined threshold, or *bad* (or *error*) state if below the threshold. Figure 1 shows an example of a typical wireless fading channel and its corresponding two-state Markov channel model. As shown in Fig. 1, the basic idea of wireless scheduling is to stop transmitting data when the channel state is in bad state during the time window $[t_1, t_2]$. This backlogged flow is compensated when the channel state is changed back to the good state in the later time window $[t_2, t_3]$. To compensate the backlogged flow, the scheduler will allow additional channel access in good state to make up the deferred data in the bad state.

The drawback of the two-state (on-off) model for wireless scheduling is the inefficiency in utilizing radio resource. For example, in the time window $[t_3, t_4]$ in Fig. 1, the scheduler will ask a user to stop transmission because of bad channel condition. In fact, the channel condition in $[t_3, t_4]$ may not be so bad that the channel can still be used to transmit data at a lower rate. On the other hand, we can transmit at higher data rate in [t2, t3] than in $[t_0, t_1]$ because channel quality in $[t_2, t_3]$ is better than that in $[t_0, t_1]$. It is obvious that the current two-state Markov model does not utilize the channel capacity efficiently. This observation motivates us to divide channel conditions into multiple states and thus propose a multi-state rate adaptation scheme for wireless scheduling.

In order to implement the proposed multi-state rate adaptation for wireless scheduling, we propose to utilize the transport format (TF) selection procedures in the MAC layer of the WCDMA system. Basically, the chip rate in WCDMA systems is fixed, while the data rate can be changed by using different spreading factors [4]. According to [5][6], spreading factor (SF) at the physical layer can be determined by selecting different transport formats in the MAC layer. Thus the problem of rate adaptation for wireless scheduling can actually be achieved by selecting an appropriate transport format (TF) in the MAC layer in every transmission time interval (TTI), i.e. 10 msec. to 80 msec.

In this paper, we propose a new TF selection procedure that incorporates all the important factors in scheduling, such as the service priority, buffer occupancy, and the number of data blocks to be sent. This new TF selection algorithm in the MAC layer combined with the multi-state rate adaptation scheme in physical layer can achieve the ultimate goals of the wireless scheduling simultaneously: (1) throughput enhancement; (2) power saving; and (3) service fairness guarantee.

The rest of this paper is organized as follows. In Section Ⅱ, we present our proposed rate adaptation scheme. In Section Ⅲ, we discuss how to use TF selection to achieve rate adaptation for wireless scheduling. Section Ⅳ shows the simulation results, and Section Ⅴ gives the concluding remarks.

Ⅱ. Proposed Multi-State Rate Adaptation Algorithm

Unlike most wireless scheduling algorithms using the two-state Markov model, we propose a multi-state rate adaptation scheme based on the cumulative density function (CDF) of the received SINR. The basic idea of the proposed multi-state rate adaptation scheme is to partition the CDF of the received SINR into multiple regions and map each region to different data rates in the rate adaptation for scheduling algorithms. In the following, we explain why different regions in CDF can represent different data rates. In the CDMA systems, the received energy of bit-to-noise density ratio, E_b/N_0, can be written as

$$\frac{E_b}{N_0} = \frac{S \cdot W}{(I+N) \cdot R_b} \tag{1}$$

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

$$PG_{dB} = 10 \cdot \log_{10}\left({}^{W}\!/_{R_b} \right) \tag{2}$$

Then, from (1) and (2)

$$\left(\frac{E_b}{N_0} \right)_{dB} = SINR_{dB} + PG_{dB} \tag{3}$$

Equation (3), implies that for a required $(E_b/N_o)_{dB}$, we can determine a suitable spreading factor or processing gain according to the received SINR.

Figure 2 shows an example of CDF of the received SINR with multiple rate adaptation regions. The key question for the multi-state rate adaptation is how to design the multiple SINR thresholds. We suggest the following procedures to determine these thresholds for rate adaptation:

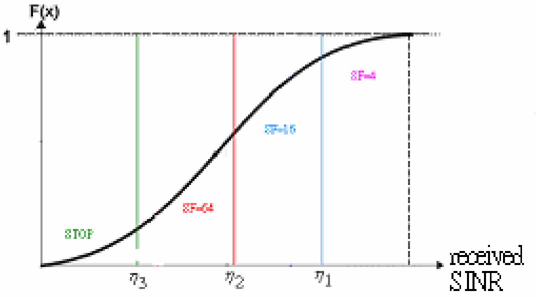

Fig. 2. An example of the CDF of the received SINR.

1. Set the required block error rate (BLER). For example, 10 % of BLER is required in the WCDMA system for moving propagation conditions as specified in [7][8].
2. Determine the corresponding E_b/N_0 for the required BLER through simulation. For BLER equal to 10 %, the required E_b/N_0 is 7 dB.
3. Based on (4), calculate the required SINR thresholds for different spreading factors.

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

where $SF_i=2^{2i}$, i=1 to 3.

By putting these thresholds into the CDF curve, we can determine the analytical average throughput as follows.

$$Throughput_{average} = \sum_i prob(state_i) \cdot Throughput(state_i) \tag{5}$$

The analytical throughput can be used to verify our simulation results.

We consider two compensation schemes for rate adaptation.

Figure 3 and 4 show the increment compensation and direct compensation for rate adaptation with 4 states, respectively.

A. Rate Adaptation with Incremental Compensation

To adapt data rate with incremental compensation, the next state of adaptation can only be one of the neighboring states or the current state itself. For example, if the current system state is in ‘SF=16’, and the SINR measurement is lower than η_2, then the next state will be state ‘SF=64’ although the measured SINR might falls in the region of state ‘STOP’ state. On the contrary, if the received SINR is higher than η_1 for the state ‘SF=16’, then the next state will be ‘SF=4’.

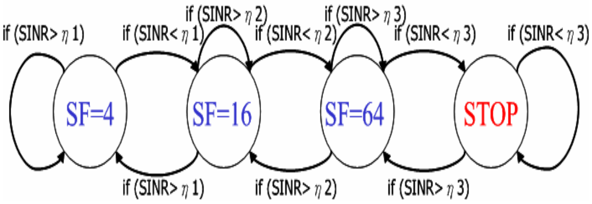

Fig. 3. Multi-state rate adaptation model with Incremental Compensation.

B. Rate Adaptation with Direct Compensation

For rate adaptation with direct compensation, the next state is the region matching the received SINR. In this case, we can increase or decrease data rate much faster so as to truly reflect the actual channel condition.

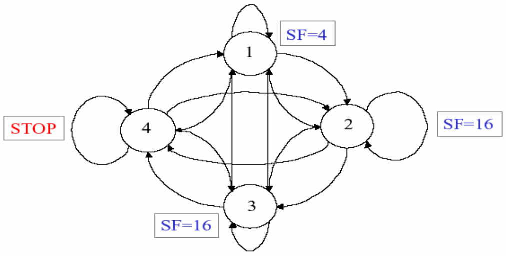

Fig. 4. Multi-state rate adaptation model with direct compensation.

Ⅲ. TRANSPORT FORMAT (TF) SELECTION

A. Background

In WCDMA systems, when we adapt data rates, we need to select a different transport format (TF) to change spreading factors. The TF is defined as a format offered by MAC to the layer1 for the delivery of a transport block set (TBS) during a transmission time interval on a transport channel. There are some attributes in each transport format:

1. Dynamic Part:
    - (a) Transport Block Size;
    - (b) Transport Block Set Size;
2. Semi-static Part:
    - (a) Transmission Time Interval;
    - (b) Error protection scheme to apply;
    - (c) Coding rate;
    - (d) Static rate matching parameter;
    - (e) Size of CRC;

By selecting different Transport Block set size as shown in Table 1[9], we can get the different spreading factors. When Transport Block Set Size changes from 320 to 5760, the number of blocks per TTI (ex.20 msec.) become 1, 2, 4, 8, and 18. So we can select different TF per TTI to match different SF. And the desired SF is based on the channel condition.

B. Proposed TF Selection Procedure

In order to utilize radio resource effectively and achieve the QoS requirement, it very critical to choose a proper Transport Format (TF). There are usually four input parameters for TF selector: 1) Buffer Occupancy (BO); 2) RLC SDU Delay; 3) service priority; and 4) link quality. BO is the number of bits in the RLC layer's buffer [10]. RLC SDU delay is the time which service's data goes through the RLC layer. A service with higher service priority will be transmitted with more radio resource (it means higher rate or serve earlier). Link Quality indicates the quality such as BER or SNR of physical layer.

Parameter	**SF=64**	**SF=32**	**SF=16**	**SF=8**	**SF=4**
Information bit rate [kbps]	32	64	128	256	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	20 ms	20 ms	20 ms	20 ms	20 ms
Transport Blocks per TTI	**1**	**2**	**4**	**8**	**18**
Type 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

Table 1. Transport Format Set in the Scheme.

Figure 5 shows the block diagram of TF selector in the MAC layer and its relation to the RRM and RRC. When the connection is established, the Radio Resource Management Controller (RRMC) will assign a group of TFs (also named TFS, transport format set) according to the type of services. Each connection has different service priority. When the data bits enter the RLC layer, they will be buffered into the queue first, and then RLC controller divides data into multiple blocks with proper size according to the TF indicated from the TF selector. The TF selector makes the decision according to the four parameters mentioned above.

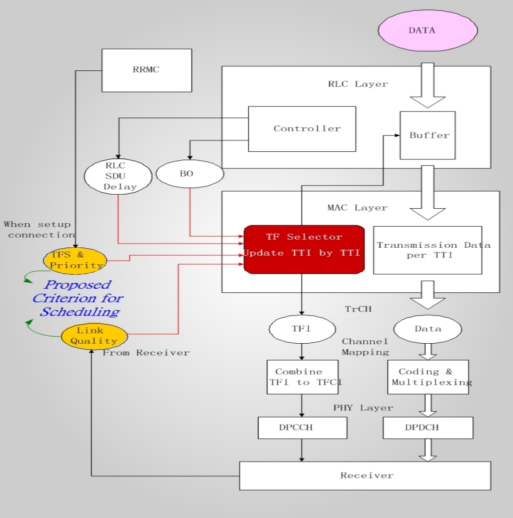

Fig. 5. System block diagram of TF selection.

Figure 6 shows the TF selection procedures.

At the setup time:

(1) RRMC will send TFS and service priority to TF selector.

At the (n-1)th frame time:

(2) After data is buffered in the queue of RLC, RLC will send primitives to TF selector including BO and RLC SDU delay.

(2) TF selector gets the link quality information from physical layer.

At the nth frame time:

(4) TF selector determines a proper TF and send to RLC layer based on the four input parameters received in the preceding frame time.

(5) RLC cut the indicated data from its queue and send it to Mac layer.

(6) TF selector sends transport blocks to physical layer and TFI for multiplexing to TFCI.

(7) At last, TFCI is sent to physical layer.

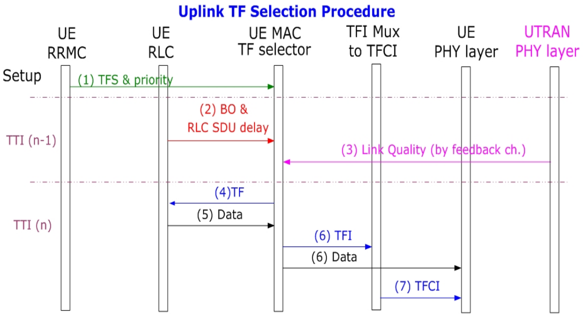

Fig. 6. TF Selection Procedures.

C. Proposed Cost Function for Multi-Service TF Selection

Basically a service with higher priority will be transmitted with more radio resource, i.e. with higher rate or to be served earlier. In the conventional system, a service with higher priority will get the total transmission resource per TTI. Thus the lower one can get the right to transmit only after the service with higher priority has an empty buffer. This strictly priority method will cause a large delay for the service with low priority and waste radio resource. For example, when the service with higher priority only has two blocks in its own buffer to be transmitted, if the channel condition actually can allow the user to transmit eight blocks at this TTI, then the strictly priority method does not utilize the radio resource efficiently since it wastes six blocks space in this TTI. This situation usually happens when the service with higher priority transmits in the lower rate than the total available rate.

In order to utilize the transport resource effectively, we propose a cost function incorporating the priority, the buffer occupancy and the number of blocks to be transmitted and apply this cost function for TF selection. The proposed cost function for TF selection is written as follow.

$$Cost = \min\left(\sum_{i=1}^{n}\left(pri_i^{\,2}\left(BO_i - TBS_i\right)\right)^2\right) \qquad (6)$$

where pri_i is i^th^ service's priority, BO_i is the i^th^ service's buffer occupancy, and TBS_i is the number of transport block sets for the i^th^ service. Based on (6) the TF selector will calculate all the possible TBS combinations among services per TTI to find the TBS combination to minimize the cost. For example, assume the total available resource is three blocks in the next TTI. Service 1 with priority 10 has two blocks in its buffer for transmitting and service 2 with priority 5 has three blocks in its buffer. Then the possible TBS combinations are listed in the following table:

Possible TBS combination	TBS_1	TBS_2	$Cost$
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

According to the definition of the cost function in (6), the TBS combination 1 has the minimum cost. Hence the TF selector will choose this TBS combination for transmitting in the next TTI.

IV. SIMULATION RESULTS

We perform simulation to evaluate the effectiveness of the proposed joint physical layer multi-state rate adaptation and MAC scheduling for single service and multiple services under a Rayleigh fading channel,

Fig. 7 shows an example of the received SINR in Rayleigh fading channel with Doppler frequency equal to 5.556. The top plot in Fig. 7 is the actual SINR, and the bottom one is the measured SIR in every TTI (i.e. 20 msec in this example).

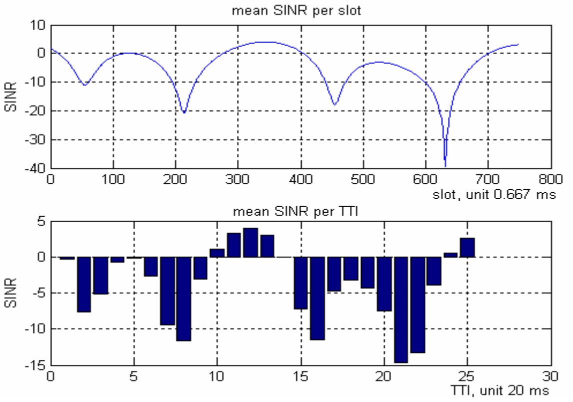

Fig. 7. An example of received SINR in a Rayleigh fading channel with Doppler frequency equal to 5.556.

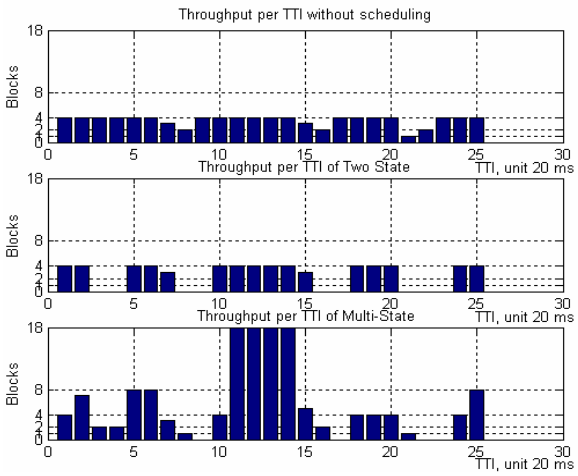

Fig. 8. Throughput comparison for different scheduling schemes assuming perfect SINR prediction in Every TTI, where TTI equal to 20 msec.

According to the channel condition in Fig. 7, Figure 8 shows the number of blocks successfully transmitted in every TTI for three cases: 1) no scheduling (top one); 2) two-state scheduling (middle one); and 3) multi-state scheduling (lowest one). In this simulation, we assume that the algorithm can perfectly estimate the mean SINR in the next TTI. In the figure, one can find that the two-state scheduling can prevent the unnecessary power consumption when channel is bad, while the multi-state scheduling not only can save power, but also improve the throughput. Table 2 lists the power consumption and throughput for two-state and multi-state adaptation normalized to the power and throughput without using scheduling. These simulations results also match the analytical results obtained from Eq. (5).

	Power	Throughput
Two-State Scheduling	81.8 %	84.81 %
Multi-State Scheduling	94.8 %	260.65 %

Table 2. Power and throughput ratio compared to the case without scheduling under perfect SINR prediction.

In practice, we cannot predict SINR perfectly for the next TTI as the case in Fig. 8. Figure 9 shows the performance of rate adaptation scheduling algorithms if the TF of the next TTI is based on the measured SIR in the current TTI. Table 3 illustrates the power consumption and throughput of the two-state and multi-state adaptation normalized to the power and throughput without using scheduling. Compared Table 2 and 3, one can see that the performance degradation due to measurement delay for one TTI is not much in our case.

	Power	Throughput
Two-State Scheduling	82.0 %	84.02 %
Multi-State Scheduling	94.8 %	258.07 %

Table 3. Power and throughput ratio compared to the case without scheduling under measurement based algorithm.

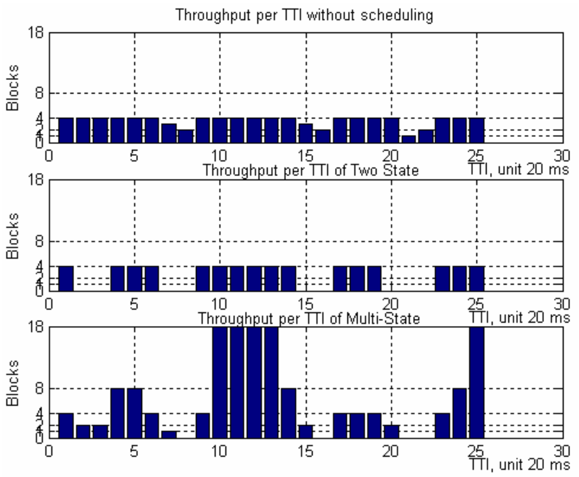

Fig. 9. Throughput comparison for different scheduling schemes based on the measured SINR.

Without using ARQ mechanism, Fig. 10 compares the performance of transmitting an image file with TF selection and that without using TF selection. The left picture is the original picture before file transmission and the other two pictures are the results without and with TF Selection under proposed multi-state rate adaptation. One can easily see the picture without TF selection will lost a lot of blocks, whereas the picture with TF Selection can adapt the channel variations, thereby resulting in better performance.

Original Bit-Map picture

Do NOT Use TFS without ARQ

Use TFS without ARQ

Fig. 10. Effect of multi-state rate adaptation on transmission of an image file.

Now we consider the performance of rate adaptation by combining TF selection with ARQ retransmission mechanism. Figures 11 and 12 show the retransmission ratio and total retransmission time respectively when we use different number of transport blocks per TTI to transmit data in Rayleigh fading channel. Here, we define the retransmission ratio as

$$Ratio_{retransmission} = \frac{T_{retransmission\_time}}{T_{total\_transmission\_time}}. \quad (7)$$

Retransmission will happen when the CRC check for a data block is detected incorrectly at receiver. In the retransmission case, the mobile will spend more TTIs to send the same data until the receiver' CRC check is correct. The higher the retransmission ratio is, the more the errors happen. One can observe that although the total transmission time is the fewest when the number of transport blocks equals 18 blocks per TTI as shown in Fig. 12, but it will also introduce a large amount of errors as shown in Fig. 11. On the other hand, although the error happens less often when the number of transport blocks is 4 and 2 blocks per TTI, they need a much longer transmission time. Now we use a TF selector to change the number of transport blocks dynamically per TTI according to channel link quality. The retransmission ratio will be just a little higher than the case using 4 transport block rate per TTI, but it can save almost 40% transmission time.

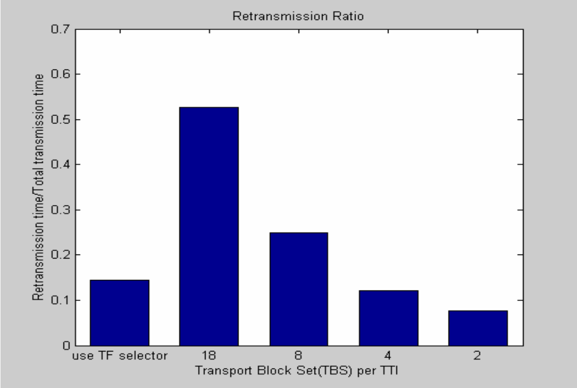

Fig. 11. Retransmission ratio with different number of blocks per TTI.

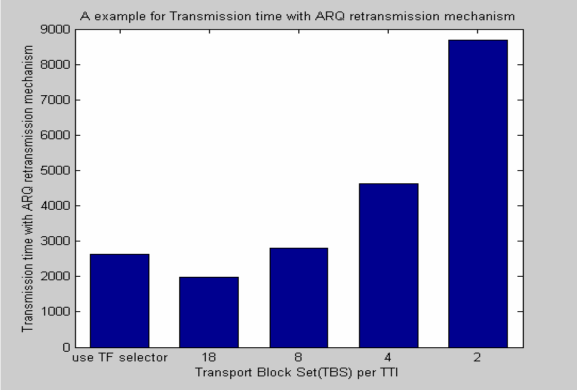

Fig. 12. Total transmission time (ms) with different number of block per TTI.

In the following, we will show the effectiveness of the TF selector for multiple services with different priorities. Here, we assume that a single user transmits two services with different priorities. Table 4 lists the selected services and their parameters. The first service is a real-time audio service, with higher priority, and the other is a normal data service with lower priority.

	Service1	Service2
Service type	Audio(real-time)	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 (from high layer)	9 blocks per 2 TTI (40ms)	9 blocks per 2 TTI (40ms)

Table 4. Services Information for Simulation

Figures 13 and 14 show the number of blocks queued in the buffer and the number of blocks available to transmit for both types of services for the conventional strict priority based TF selection. Figures 15 and 16 illustrate the performance based on our proposed cost function based TF selection. For service 1 the queue length and service time in both systems are similar, but the queue length in buffer 2 in Fig. 15 is significantly less than that in Fig. 13 (about 60%). Furthermore, the service time for service 2 in Fig. 16 is also less than that in Fig. 14 (about 20%).

These results indicate that our algorithm can utilize the available transport blocks more effectively and achieve weighted fairness between different services. This is because we take into account not only the priority but also buffer occupancy to minimize the cost function. Hence, the service with higher priority will be assigned more transport blocks to reduce the cost. On the other hand, when the service's buffer with lower priority is too large such that the cost increases drastically, this algorithm also assigns transport blocks to the service with lower priority. Consequently, the buffer queue will be reduced.

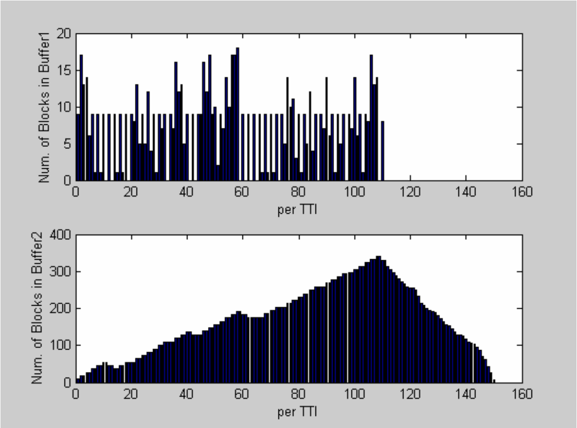

Fig.13. Buffer occupancy for each service with conventional strict priority based scheduler.

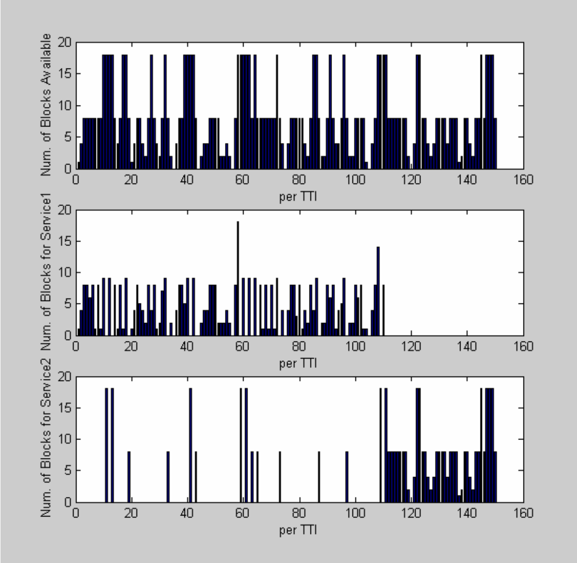

Fig.14. Available transport resource with conventional strict priority based scheduler.

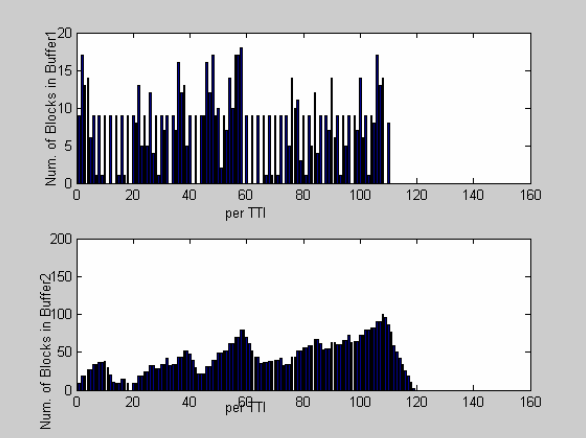

Fig. 15. Buffer Occupancy with proposed cost-function based MAC Scheduler.

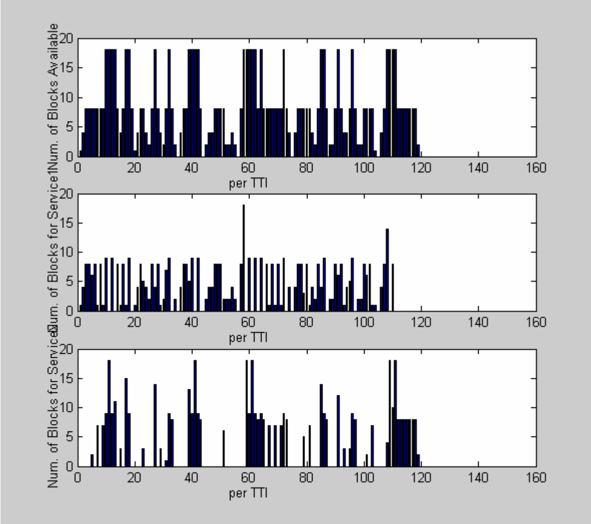

Fig. 16. Available transport resource with proposed cost-function based MAC scheduler.

V. CONCLUSION

In this paper, we proposed a new multi-state channel model for MAC scheduling and rate adaptation in the WCDMA system. This multi-state channel model for MAC scheduling is developed based on the cumulative density function of the received SINR in the physical layer. According to this model, a set of multiple thresholds can be determined to adapt channel variations and change spreading factors via the transport format selection procedures in the MAC layer.

Moreover, we proposed a new cost function based selection procedures to incorporate all the important factors in scheduling, such as service priority, buffer occupancy, and the number of data blocks to be sent. This new TF selection algorithm in the MAC layer combined with the multi-state rate adaptation scheme in physical layer can achieve the ultimate goals of the wireless scheduling simultaneously: (1) throughput enhancement; (2) power saving; and (3) service fairness guarantee.

One possible research topic extended from this work is to consider the impact of faster channel variations and to incorporate other channel quality prediction schemes to the rate adaptation scheme for variable spreading factors multi-rate CDMA systems or adaptive modulations based multi-rate CDMA systems.

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