Fair & Power-Efficient Channel-Dependent Scheduling for CDMA Packet Networks

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Abstract--Recently, there has been a significant increase in the amount of packet data services, such as web browsing, being offered over mobile phones. Data services are expected to account for the highest volume of traffic soon. However, current downlink scheduling algorithms for packet data services cannot achieve fairness and power efficiency at the same time. In this paper, we propose a novel scheduling algorithm called Fair & Power-Efficient Channel-Dependent Scheduling which schedules packet delivery to mobile stations in a fair manner and at the same time takes into consideration the channel conditions for power efficiency. The performance study shows that this approach is indeed fair as well as energy conserving and consequently reduces interference.

Keywords: CDMA, downlink, packet data, power-efficient, Rayleigh fading

1. Introduction

Nowadays, packet data services, such as web browsing and instant messaging for personal wireless communication, have become more popular. Furthermore, packet data services have been standardized in the 3rd generation (3G) wireless systems [1], where code division multiple access (CDMA) is going to be widely deployed as the air interface [2]. Thus resource allocation and quality of service (QoS) support for packet data traffic over CDMA networks becomes very important. Current scheduling algorithms on the downlink are optimized mainly for voice traffic and are not suitable for packet data traffic. It is therefore necessary to investigate downlink scheduling algorithms for packet data.

The base station is responsible for scheduling and delivering packets to the corresponding mobile stations that are within its transmission range. The goal of the scheduler is to serve active mobile stations in a fair manner and also to take into account the physical factors that may affect a wireless connection. Physical factors such as differences in distance, signal propagation (e.g., shadowing), and multipath fading can all lead to varying channel conditions [3]. The scheduler can take advantage of these changing channel conditions by serving a mobile station at times when the channel conditions to that mobile station are good. Such utilization of good channel conditions will result in an increase in system capacity. At the same time, the scheduler must be fair and not favor the mobile stations with good channel condition only. Otherwise, mobile stations with weak channels will face starvation.

Previous work done in this area either focuses primarily on fairness without exploiting the wireless channel conditions, or on channel utilization without providing fairness. A simple round-robin based and fair-queuing based scheduling mechanism [4] can not take advantage of changing channel conditions. The scheduling scheme may try to send data during times of poor channel conditions, resulting in either the need for increased transmit power or decreased data rates. On the other hand, scheduling mechanisms that take channel conditions into account [5][6][7] tend to be unfair. These algorithms may defer packet delivery to nodes with unfavorable channel conditions while serving other nodes. Nodes that are positioned closer to the base station get better treatment than those further away. A more comprehensive survey regarding scheduling algorithms may be found in [8].

In this paper, we propose a novel scheduling technique called Fair & Power-Efficient Channel-Dependent Scheduling (FCDS), which ensures long-term fairness while at the same time exploiting the changing channel conditions. Its purpose is to provide a fair service to all mobile stations, while minimizing the used transmit power thereby increasing the system capacity at the same time.

The rest of the paper is organized as follows. In section 2, we present the proposed Fair & Power-Efficient Channel-Dependent Scheduling (FCDS) technique. The performance of our scheduling scheme is evaluated in Section 3. Finally, we conclude this paper in Section 4.

2. The Proposed FCDS Scheme

In our scheme, the base station keeps track of the channel quality to each mobile station within its transmission range. We infer the channel quality from the transmitted power; high quality channels need less transmit power than low quality ones to meet the same Signal-to-Interference-Ratio (SIR) requirement. A moving average of the transmitted power used for each mobile station is maintained. Power fluctuations that may inadvertently affect the moving average are dealt with by maintaining a moving variance for each mobile node. The base station uses these moving averages as well as the moving variances to make its scheduling decisions. We have shown that such decisions tend to be much fairer than the ones based solely on the absolute transmitted power because they do not favor nearby mobile stations with high quality channels. In the following, we present a detailed model to show how the scheduler works.

Suppose a base station is serving n ($n \geq 2$) mobile stations on a downlink channel using a hybrid CDMA/TDMA transmission scheme [9][10]. Furthermore, assume that at a certain time slot t, packets are queued and wait for transmission to m ($0 \leq m \leq n$) active mobile stations. For simplicity, we assume only one packet can be sent in each time slot. It can be easily generalized to multiple transmissions per slot duration. We use the transmitted power to represent the channel quality because power control is essential in CDMA systems. The base station can get fast feedback information from the receiver side, where the transmitting node dynamically adapts its transmitted power to the current channel conditions so that the received power or SIR at the receiver is constant. As a result, the required transmit power is a good estimate of channel conditions.

A scheduler can therefore use the transmitted power to decide which mobile station to send packets to next. One way to do this is to compare the transmitted powers for each of the m mobile stations with packets queued for transmission and select the mobile station which has the lowest transmitted power. This approach is referred to as Best-Channel-First (BCF) and is often used as the baseline for comparison. BCF is unfair since it generally favors mobile stations that are physically located nearby the base station since they require less transmit power. In order to compensate for this, our scheduler keeps track of the moving average of the transmitted power for each mobile node. This moving average reflects the transmitted power used for each mobile station in the recent past. This information, along with the current transmitted power can be used by the base station to make the scheduling decision.

The exponentially weighted moving average $\hat{\mu}_{i,t}$ is a weighted value of previous transmitted powers along with the current transmitted power and is given as:

$$\hat{\mu}_{i,t} = (1-\alpha_1)\hat{\mu}_{i,t-\Delta t} + \alpha_1 \overline{p}_{i,t} \qquad (1)$$

where $\overline{p}_{i,t}$ is the transmitted power used to transmit to node i at time t, t is the interval with which the average is updated, we assume it is one time slot duration here and α_1 ($0 < \alpha_1 < 1$) is the parameter determining the weight of the current power compared to the previous power.

The scheduler uses $\overline{p}_{i,t}$ and $\hat{\mu}_{i,t}$ to make a decision. A possible approach is to schedule a mobile node that requires the least transmitted power relative to its moving average, that is, $\overline{p}_{i,t} - \hat{\mu}_{i,t}$. This approach is fair in the sense that mobile stations far away are treated equally to those nearby. However, it does not compensate for fluctuations in power. It favors mobile nodes with less power fluctuations. To compensate for this, we keep track of the degree of power fluctuations experienced in the past by maintaining a moving variance for each mobile node.

The moving variance $\hat{\sigma}_{i,t}{}^2$ for the transmitted power is given as:

$$\hat{\sigma}_{i,t}{}^2 = (1-\alpha_2)\hat{\sigma}_{i,t-\Delta t}{}^2 + \alpha_2(\overline{p}_{i,t} - \hat{\mu}_{i,t})^2 \qquad (2)$$

where α_2 ($0 < \alpha_2 < 1$) is a weighting parameter.

Finally, the scheduler takes the current transmitted power $\overline{p}_{i,t}$, the moving average $\hat{\mu}_{i,t}$, and the moving variance $\hat{\sigma}_{i,t}{}^2$ to compute the normalized transmitted power $Z_{i,t}$. The mobile station with the smallest normalized transmitted power H_t (as show in Equation 3) will be selected to transmit in the time slot t.

$$H_t = \min_{1 \leq i \leq m} \{ Z_{i,t} = (\overline{P}_{i,t} - \hat{\mu}_{i,t}) / \hat{\sigma}_{i,t} \} \qquad (3)$$

The operation of FCDS can be illustrated by the Pseudo code given in Figure 1.

FCDS Algorithm:

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When packets arrive, they are queued and are waiting for transmission to m active mobile stations.
At each time slot t,
    For each active mobile station i (i= 1,..., m):
        Update $\hat{\mu}_{i,t}$ according to (1).
        Update $\hat{\sigma}_{i,t}^2$ according to (2).
        If there is a packet to mobile station i,
            Compute the normalized transmit power
                $Z_{i,t} = (\overline{p}_{i,t} - \hat{\mu}_{i,t}) / \hat{\sigma}_{i,t}$
The Base station scheduler selects the mobile station with the smallest $Z_{i,t}$ and delivers the packet
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Figure 1. Pseudo code for FCDS scheduling algorithm

3. Performance Evaluation

We evaluate the performance of FCDS based on two criteria --- power conservation and fairness. It is not possible to achieve both goals simultaneously since enhancement to one implies degradation to the other. As a result, our approach reaches a compromise between the two; it utilizes the channel efficiently while trying to be fair at the same time. We prove that our approach is power efficient through theoretical analysis and simulation results in Section 3.1. Then, in section 3.2, we show through comparative simulations that our approach is fairer than BCF.

A discrete event-driven simulator is used to study the characteristics of FCDS. The system architecture is illustrated in Figure 2. The base station maintains one queue for each active user. When packets arrive, they will be put into one of these queues based on their destinations. In the simulation, only fast fading is considered. The weighting parameter α_1 and α_2 are set to be 0.1 in our simulations.

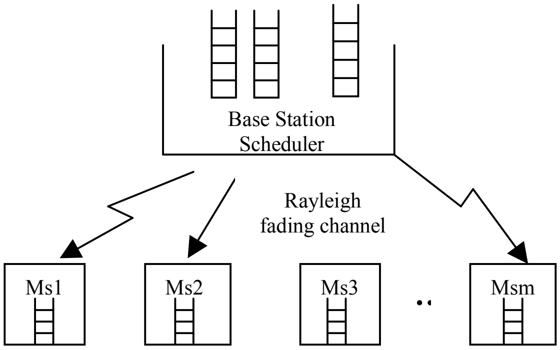

Figure 2. System architecture for CDMA downlink scheduling

3.1 Power Conservation

As mentioned previously, the required transmit power to mobile station *i* at time *t*, is a good measure to represent the current channel conditions. If, instead, we assume no power control is used and the transmitted power for each mobile station is fixed, then the received power can also be used to reflect the channel conditions. Higher received power can be interpreted as a better channel condition when transmit power is fixed. Let the received power $p'_{i,t}$ for mobile station *i* at any time *t* be described by the random variable $X_{i,t}$ with an average $\mu_{i,t}$ and variance $\sigma_{i,t}{}^2$.

Let the random variable $Y_{i,t}$ represent the normalized received power, i.e.,

$$Y_{i,t} = \frac{X_{i,t} - \mu_{i,t}}{\sigma_{i,t}} \tag{4}$$

For this scenario, the scheduler will select the packet to transmit to the mobile station with the maximum received power:

$$W_t = \max_{1 \le i \le m} Y_{i,t} \tag{5}$$

where the random variable W_t represents the normalized received power at the selected mobile station at time *t*. The random variables $Y_{i,t}$ (for all *i*) are independent and identically distributed (i.i.d). A mobile station *i* will receive the normalized power according to random variable W_t, if a packet to that mobile station is scheduled at time *t*. By reversing the translation and normalization, we can construct the random variable $V_{i,t}$ that describes the real received power:

$$V_{i,t} = W_t \sigma_{i,t} + \mu_{i,t} \tag{6}$$

Here we define the expected gain to demonstrate how power is conserved. The expected gain g_i for mobile station *i* can be denoted as

$$g_i = \frac{E(V_{i,t})}{E(X_{i,t})} = E(W_t)\frac{\sigma_{i,t}}{\mu_{i,t}} + 1 = E(W_t)c_{X_{i,t}} + 1 \tag{7}$$

where $c_{x,t}$ is the coefficient of variation of the distribution of $X_{i,t}$. The expected gain is achieved by receiving packets when channel conditions are good, rather than receiving at any arbitrary time *t*.

For a Rayleigh fading channel, we are able to find an explicit expression for g_i. In this case, the probability density function (pdf) of the envelope of the received signal is described as:

$$f_U(u) = \frac{u}{b^2} e^{-\frac{u^2}{2b^2}} \quad ,u \ge 0 \tag{8}$$

And the cumulative distribution function (cdf) is

$$F_U(u) = 1 - e^{\frac{-u^2}{2b^2}} \quad ,u \ge 0 \tag{9}$$

Since the power is the square of the envelope, the received power $X_{i,t}$ has an exponential distribution with cdf

$$F_{X_{i,t}}(x) = 1 - e^{\frac{-x}{2b^2}} \quad ,x \ge 0 \tag{10}$$

For this distribution, the following holds:

$$\mu = \sigma = 2b^2 \tag{11}$$

So, for the distribution of $Y_{i,t}$,

$$F_{Y_{i,t}}(y) = F_{X_{i,t}}(\sigma y + \mu) = 1 - e^{-y-1}, y \ge -\frac{\mu}{\sigma} = -1 \tag{12}$$

Note that $F_{Y_{i,t}}(y)$ is independent of *b*. For the maximum of a number of i.i.d random variables, the cdf is the product of their cdf's, i.e.,

$$F_{W_t}(w) = \prod_{i=1}^{m} F_{Y_{i,t}}(y) = (1 - e^{-w-1})^m \quad ,w \ge -1 \tag{13}$$

To find the gain, we have to derive the expected value of W_t:

$$E(W_t) = \int_{w=-1}^{\infty} wf(w)dw \tag{14}$$

where $f(w)$ is the pdf of W_t, i.e.,

$$f(w) = \frac{dF_{W_t}}{dw} = me^{-w-1}(1-e^{-w-1})^{m-1} \tag{15}$$

Taking the expectation, we get

$$E(W_t) = \int_{w=-1}^{\infty} wme^{-w-1}(1-e^{-w-1})^{m-1}dw = -1 + \sum_{k=1}^{m}\frac{1}{k} \tag{16}$$

and

$$g_i = \sum_{k=1}^{m}\frac{1}{k} \tag{17}$$

Equation (17) gives the analytical bound of expected gain for a Rayleigh fading channel, which is plotted as the solid line in Fig. 3. A simulation study was also conducted in which the transmitted power was fixed and the received power at each mobile station was normalized. Then the mobile station with the maximum normalized received power, is selected to transmit. The simulation result for the expected gain is illustrated by the dotted line in Figure 3. The expected gain shows that if the transmitted power is fixed, much more power can be received when the channel conditions are taken into account and the data is transmitted during good channel state instead of transmitting the packet at any arbitrary time. Consequently, to achieve a fixed power or SIR requirement at the receiver side, we can use less transmitted power. Therefore, power is conserved by utilizing information regarding the channel condition as in FCDS. The higher the expected gain is, the more power that can be conserved.

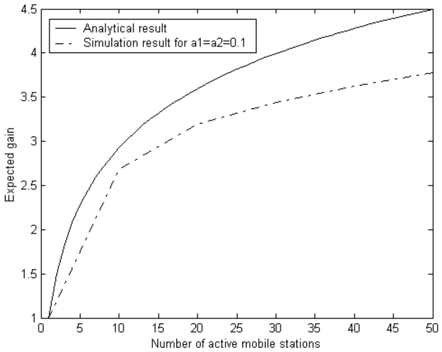

Figure 3. Analytical and simulation results of expected gain for FCDS (in terms of received power)

In a practical system, power control is usually implemented. The transmitted power is adjusted to adapt to channel conditions so that the received power is just above an acceptable threshold. Therefore, the expected gain is now calculated in terms of the transmitted power. Power control is simulated by adjusting the transmitted power in increments of 1dB with feedback information from the receiver side. The scheduling decision is therefore based on the normalized transmitted power. Simulation results for both FCDS and BCF are shown in Figure 4. Again, the expected gain reflects how much power is conserved. From Figure 4, we can see that both FCDS and BCF conserve much power by utilizing channel conditions when making scheduling decisions. Since BCF always selects the packet with best channel condition to transmit, it conserves more power than FCDS; however, it is not fair.

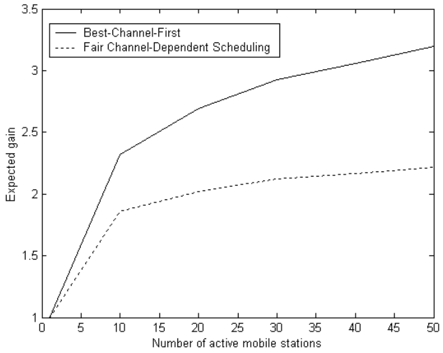

Figure 4. Comparison of expected gain for BCF and FCDS (in terms of transmitted power)

3.2 Performance Evaluation of Fairness

As stated before, a good scheduler should consume less power by utilizing channel condition information and at the same time, provide fair service to each mobile station. In this section, we evaluate another important criteria---fairness. Two performance metrics are used, one is called scheduling probability and the other is the incurred delay. The former reflects if each mobile station has equal chance to transmit in the long run, while the latter shows if the packets to each mobile station experience similar delay.

Scheduling probability. We define the scheduling probability Q_i for mobile station *i* as the probability that a mobile station is selected to transmit. Then the coefficient of variation (*cov*) of this probability is used to reflect the fairness of the scheduling scheme.

$$cov = \frac{std}{mean} = \frac{\sqrt{\sum_{i=1}^{m}(Q_i - \overline{Q})^2}}{\sqrt{N\overline{Q}}} \tag{18}$$

where $\overline{Q}$ is the mean of Q_i for $i=1$ to m.

If the scheduling scheme is relatively fair, then each mobile station has similar chance to transmit, so the *cov* of the scheduling probability should be small. The smaller the *cov* is, the fairer the scheduling is. From Figure 5, we observe that FCDS demonstrates significantly more fairness than BCF. The *cov* for BCF is from 31% to 46%, while for FCDS, it is much lower ranges from 6% to 16%.

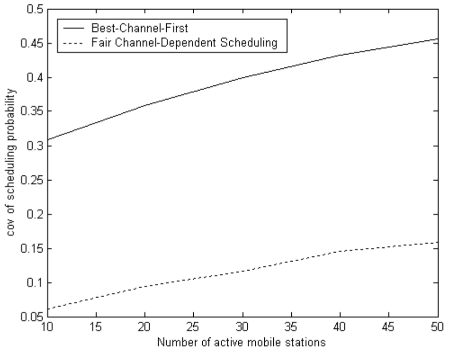

Figure 5. *cov* of scheduling probability comparison for BCF and FCDS

Average queueing delay. Another parameter, average queueing delay is used to evaluate fairness. As introduced earlier, the base station maintains one queue for each active mobile station. The average packet delay, along with the standard deviation for each queue is collected. The confidence intervals for the queueing delay reflect fairness. Fair scheduling scheme makes packets in each queue experience similar delay. So the confidence interval is tightly bounded. The narrower the confidence interval is, the fairer the scheme is. Figure 6 demonstrates again that our FCDS is fairer than BCF by having a narrower 95% confidence interval.

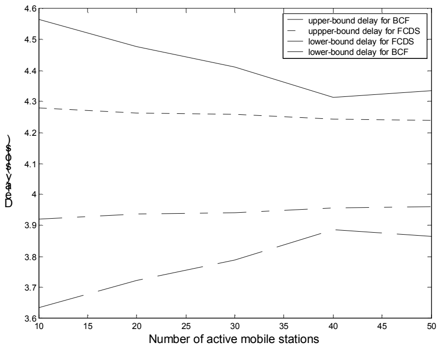

Figure 6.Confidence interval of the queueing delay for BCF and FCDS

4. Conclusion

We have presented a Fair & Power-Efficient Channel-Dependent scheduling algorithm for packet data on the CDMA downlink in this paper. This algorithm not only utilizes the changing channel condition to conserve transmitted power and consequently reduce interference, but also provides fairness to each mobile station. We compared the performance of our approach to another simple channel-dependent scheme BCF. Our algorithm exhibits much more fairness than BCF, and it balances power efficiency and fairness.

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5. References

[1] Niranjan Joshi, Srinivas R. Kadaba , Sarvar Patel, Ganapathy S. Sundaram " Downlink scheduling in CDMA data networks," Proceedings of the sixth annual international conference on Mobile computing and networking, August 2000.

[2] "Global CDMA Business Opportunities," Telecom reports by Datacomm Research Company, published August 1, 2000.

[3] P. M. Shankar, Introduction to Wireless Systems, John Wiley & Sons, Inc. publishers, Chapter 2.

[4] S. Lu, V. Bharghavan and R. Srikant, "Fair Scheduling in Wireless Packet networks," *IEEE/ACM Transactions on Networking*, Vol. 7, Issue 4, August 1999, pp. 473-489.

[5] Kenneth S. Lee and Magda El Zarki, "Comparison of Different Scheduling Algorithms for Packetized Real-Time Traffic Flows," *Proceedings of 4th International Symposium on Wireless Personal Multimedia Communications (WPMC'01),* Aalborg, Denmark, September 9 - 12, 2001.

[6] Xin Liu, Edwin K.P. Chong and Ness B. Shroff, "Opportunistic Transmission Scheduling With Resource-Sharing Constraints in Wireless Networks," *IEEE Journal on Selected Areas in Communications*, Vol. 19, No. 10, October 2001.

[7] K. Kumaran and P. Whiting, " Rate Processor Sharing: A Robust Technique for Scheduling Downlink Data Transmissions in CDMA Wireless," *Technical Report BL0112120-990809-17TM*, Bell Labs, 1999.

[8] Yaxin Cao and Victor O.K. Li, "Scheduling Algorithms in Broad-band Wireless Networks," *Proceedings of the IEEE*, Vol. 89, No. 1, January 2001.

[9] E. Brand and A. Hamid Aghvami, "Multidimensional PRMA with Prioritized Bayesian Broadcast – A MAC Strategy for Multiservice Traffic over UMTS," *IEEE Transactions on Vehicular Technology*,, Vol. 47, November 1998, pp. 1148-61.

[10] T. Ojanperä, "FRAMES – Hybrid Multiple Access Technology," *Proceedings of ISSSTA,* Mainz, Germany, September 1996, pp. 320-4.