PERFORMANCE IMPACTS OF ERRONEOUS CHANNEL PREDICTIONS ON PACKET SCHEDULING IN WIRELESS NETWORKS

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ABSTRACT

Current and next-generation wireless networks take advantage of scheduling techniques such as the Proportional-Fair (PF) algorithm to achieve multi-user diversity over time-varying wireless channels and thus high system throughput. In this paper, we examine how inaccurate channel-quality predictions can lead to significant performance degradation of the packet scheduler. We propose to use a Wiener-filtering method to accurately predict the maximum supportable data rate in a future time slot for each user, which serves as input parameters for the PF scheduler. Our simulation results reveal that the scheduler coupled with the Wiener-filtering predictions can provide significant performance improvement in terms of users' received signal-to-noise ratio (SNR), error rate and packet delay over two commonly used prediction methods, namely, the extrapolation and exponential-smoothing methods.

Keywords: Channel prediction, Packet scheduling, Proportional fair, Wireless networks.

I. INTRODUCTION

Current and next-generation wireless networks make use scheduling techniques to explore multi-user diversity for achieving high system throughputs for wireless data applications. One particularly attractive strategy is to schedule data transmission based on the relative channel quality of different users, while aiming for an acceptable balance between system performance and fairness among users. A well-known algorithm that accomplishes this goal is the Proportional Fair (PF) scheduling, which is, for example, implemented in CDMA 1X EV-DO systems [1] [2]. The theoretical performance of the PF algorithm is analyzed in [3].

To efficiently utilize limited radio resources, existence of multiple users in the system and time variability of channel quality for various users makes it possible to achieve performance gains by adopting suitable algorithms for packet scheduling. Specifically, a scheduler decides to which user the next time slot is allocated according to a performance metric. At the beginning of each time slot, the scheduler updates the metric values of all ready users, and chooses the one with the maximum value to serve in the following time slot. As a consequence, the effectiveness of the scheduling algorithm strongly depends on the accuracy of the performance metric, or to what extent the metric represents the "benefit" the system gains from scheduling the particular user. As far as the PF scheduling is concerned, it allocates system resources according to the future channel quality for different users. Therefore, the accuracy of future channel-quality predictions is essential to achievement of the desirable performance of the PF scheduler.

To the best of our knowledge, although the PF scheduler has been studied extensively and implemented in practical systems, not much attention has been paid to examine how the scheduler is affected by inaccurate channel-quality predictions. In practice, the PF scheduler typically makes use of simple channel prediction methods such as: a) extrapolating the channel quality (in terms of e.g., supportable data rate) for the current slot as that for a future slot, and b) applying an exponential smoothing technique to predict channel quality for a future slot. The performance of the PF scheduler clearly depends on the accuracy of such prediction algorithms, which in turn is highly dependent on the variation of channel quality. If the radio signal undergoes severe multi-path fading or the mobile terminal moves at a high speed, the high variation of the channel quality can lead to significant performance degradation of the PF scheduler using such simple prediction methods. It is particularly so if a large delay is incurred for mobile terminals to feedback channel-quality information to the associated base station.

In this paper, we present a first study of performance impacts of erroneous channel predictions on the PF scheduler. Furthermore, we observe that there is potential gain if we apply sophisticated channel prediction algorithms rather than the simple extrapolation and exponential smoothing techniques, especially in the case of long feedback delay. In particular, we propose to enhance the PF scheduler by adopting appropriate prediction algorithm, i.e., the Wiener Filtering (WF) method, and assess its performance improvement for the PF scheduler in terms of received signal-to-noise ratio (SNR), bit-error rate (BER) and packet delay.

The remainder of the paper is organized as follows. In Section II we provide further motivation for our enhanced algorithm after investigating the impacts due to erroneous predictions of future channel quality. Section III presents the channel-prediction algorithm for the enhanced packet scheduling. Numerical results and discussions are presented in Section IV. Finally, Section V presents our conclusion of this study.

II. IMPACT OF ERRONEOUS CHANNEL-PREDICTION

In this section, we investigate the PF algorithm in greater detail by concentrating on the accuracy issue of the future channel quality. First, let us briefly summarize the operations of the standard PF algorithm [2]. The system is time-slotted, and in time slot n, each user (or terminal) i reports his/her estimated maximum transmission rate, $\widehat{R}_i[n+1]$ (in bits/sec), which can be reliably supported in the next slot n+1. The scheduler then determines the user with the largest scheduling metric defined as

$$M_i[n+1] = \frac{\widehat{R}_i[n+1]}{T_i[n+1]} \tag{2.1}$$

where $T_i[n+1]$ is the smoothed data throughput of user *i* up to slot n+1, and it is calculated as

$$T_i[n+1] = \begin{cases} (1-\frac{1}{t})T_i[n] + \frac{1}{t}\widehat{R}_i[n] & \text{if user i served in slot n} \\ (1-\frac{1}{t})T_i[n] & \text{otherwise} \end{cases} \tag{2.2}$$

where *t* is an adjustable parameter and the typical value for t is 1000.

Now let us examine how to calculate $\widehat{R}_i[n+1]$ for each user. In this paper, we assume that the supportable data rate is only influenced by the instantaneous SNR. According to [9], the data rate is related to the SNR through

$$R = B\log_2(1+SNR) \tag{2.3}$$

That means that the supportable data rate is approximately proportional to the SNR in dB, assuming that data rates are not constrained to be certain discrete values. Therefore we only have to predict $SNR_i[n+1]$ for each user.

Consider a CDMA system and its equivalent low-pass discrete-time system model at the output of the matched filter and sampler given by

$$y_k = c_k b_k + z_k$$

where c_k is the multiplicative fading coefficient for the k-th chip, b_k is modulated data sequence, and z_k is the complex discrete AWGN process with the variance of $N_0/2$. Let us consider Wideband CDMA (WCDMA) systems [7] as an illustrative example. Each time slot consists of 2560 chips. To reduce computation complexity, we suggest taking $K = 20$ samples out of the 2560 chips in a slot to estimate the instantaneous rate feasible in that slot. That is, the sampling rate is 30 kHz, which is still much larger than the Doppler frequency for typical vehicle speed. According to [8], as long as the sampling rate is bigger than twice of the maximum of Doppler frequency, the proposed sampling rate for channel predictions is applicable to typical fading channels. Let $c_{k,i}[n]$ denote the *k*-th sampled value of the *i*-th user in slot *n*. Then the averaged SNR for that slot is obtained by

$$SNR_i[n] = \frac{1}{K}\sum_{k=1}^{K}\left|c_{k,i}^2[n]\right| \cdot SNR_A \tag{2.4}$$

where K is the number of samples in a slot and $K = 20$ in the simulation study in Section IV. SNR_A represents the level of background Additive White Gaussian Noise (AWGN). Therefore, the random variables to be predicted by channel prediction algorithms are $c_{k,i}[n+1]$'s for *k*=1 to *K* for given user *i* and slot *n*.

The extrapolation method for channel predictions with d-slot feedback delay can be expressed as

$$\widehat{c}_{k,i}[n+1] = c_{k,i}[n-d] \tag{2.5}$$

where $\widehat{c}_{k,i}[n+1]$ and $c_{k,i}[n-d]$ are the predicted value of the *k*-th sample of user *i* for slot $n+1$ and the exact value of the *k*-th sample of user *i* for slot $n-d$, respectively. With the same notation, the exponential-smoothing method for channel predictions can be written as

$$\widehat{c}_{k+1,i}[n+1] = (1-\alpha)\cdot\widehat{c}_{k,i}[n+1] + \alpha\cdot c_{k,i}[n-d] \tag{2.6}$$

where α is constant between 0 and 1. Our extensive experiments reveal that the best performance can be obtained when α is set to 0.9 for the parameter settings considered in Section IV.

After obtaining $\{\widehat{c}_{k,i}[\mathrm{n}+1], \quad k = 1\cdots K\}$, the SNR for the next slot can be calculated by (2.4) and then following the proportionality between SNR (in dB) and data rate as in (2.3), we can identify the supportable data rate for the next time slot for each user *i*.

Let us now examine impacts of these two simple prediction methods on the performance of PF scheduler through simulation results. We focus on users' received SNR. That is, we record the actual SNR value of the scheduled user slot by slot, and average them over a long time. It is natural that different channel prediction algorithms lead to different levels of received SNR. To form a baseline for comparison, imagine that there is an ideal predictor, by which we know the exact future channel quality in advance. Since the scheduler equipped with the ideal predictor never makes wrong scheduling decisions, using the ideal predictor yields the upper limit of the scheduling performance. To quantify the degradation due to other predictions algorithms, we examine the difference between the received SNR of the users scheduled based on the previously mentioned channel prediction algorithms and that of the users scheduled based on the ideal channel predictor.

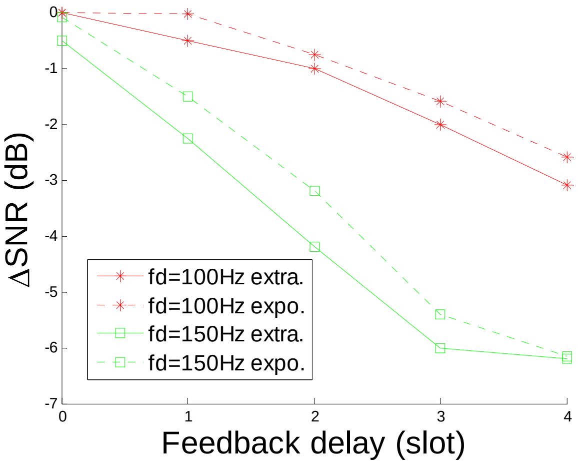

Fig. 2.1 Degradation of received SNR due to erroneous channel predictions.

Figure 2.1 shows that the difference in received SNR

$$\Delta SNR = SNR_E - SNR_I \tag{2.7}$$

where SNR_E and SNR_I are the received SNR associated with the erroneous and ideal prediction algorithms, respectively. As shown in the figure, the SNR difference is negative in the whole range of the feedback delay, which means that both the extrapolation and the exponential methods cause performance degradation in terms of received SNR. Furthermore, loss in SNR is rapidly increased as the feedback delay increase. It is seen that with feedback delay of 4-slot and Doppler frequency of 150 Hz (corresponding to 81 km/hr), the loss of SNR could be as large as -6 dB. In communication system using typical modulation schemes, -6 dB SNR loss is not trivial. For example, in an uncoded Binary DPSK modulation, the theoretical BER-SNR curves are presented in Fig. 2.2 (the solid line). To achieve, for example, an operational system with BER of 10^{-6}, the required SNR is 11dB for an AWGN channel. For a channel-prediction algorithm causing a SNR loss of 6 dB, the BER increases to about 10^{-2}, which is definitely unacceptable for practical use.

These results motivate us to adopt appropriate algorithms for accurate channel predictions for efficient packet scheduling in broadband wireless networks. Towards this goal, we propose to apply Wiener filtering to enhance predictions of channel quality as follows.

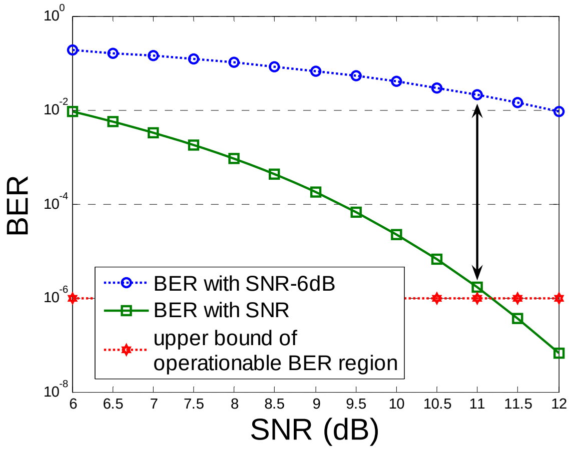

Fig. 2.2 Theoretical BER-SNR performance for uncoded binary DPSK modulation.

III. WIENER FILTERING

Recent work in channel modelling and prediction has shown the feasibility of predicting Rayleigh fading channels over horizons of up to several ms with reasonable accuracy [8]. Evidently, this prediction range is enough for the PF scheduler in certain networks such as the W-CDMA systems where the slot length is 666 μs.

We consider a Wiener-filtering algorithm for the PF scheduler as follows. After obtaining estimates of all $\hat{c}_{k,i}[n+1]$, $SNR_i[n+1]$ is computed from (2.4) and the instantaneous rate $R_i[n+1]$ is then estimated according to Shannon's theorem [9]. Based on the estimated data rate, the PF scheduler chooses the user with the largest scheduling metric according to (2.1) to serve in the next slot.

In terms of Wiener filter, it is dealing with the problem of finding the minimum mean squared estimate (MMSE) of $\hat{c}_k$ using a linear combination of K signal values from past K values [10]. The multiplicative fading coefficient c_k is modelled as an auto-regressive (AR) model with order K in the form of

$$\hat{c}_{k,i}[n+1] = \sum_{j=0}^{K-1} \alpha_{\beta}(j) c_{K-j}[n-d] \tag{3.1}$$

$$\beta = k + (d-1) \cdot K \tag{3.2}$$

where $\alpha_{\beta}(j)$ denotes the j-th tap coefficient of the Wiener FIR filter in the β-step prediction. For each prediction, we use all c_k's for time slot *n-d* to predict $\hat{c}_k$ for *k=1* to *K* for the slot *n+1*, given that there is *d*-slot feedback delay for the transmission of channel state information (from each user to the base station). The k -th value in the next slot are predicted by a so-called β -step prediction. The optimal coefficients $\alpha_\beta(j)$ are calculated as

$$\vec{\alpha}_\beta = \mathbf{R}_x^{-1}\vec{r}_\beta \qquad (3.3)$$

where $\mathbf{R_x}$ is the auto-correlation functions of $\{c_k\}$, and the k-th element of $\vec{r}_\beta$ is defined as

$$r_\beta(k) = \mathrm{E}\left\{c(n+\beta)c^*(n-k)\right\} = r(\beta+k)\ . \qquad (3.4)$$

The satisfactory prediction of channel's fading coefficients by Wiener filtering is shown in Fig 2.3. Each slot contains 20 samples, and the filter predicts the next 20 samples based on current slot. The first and second groups of 20 samples in the figure correspond to time slot 1 and 2 respectively. Likewise, the subsequent coefficients are associated with the follow up time slots.

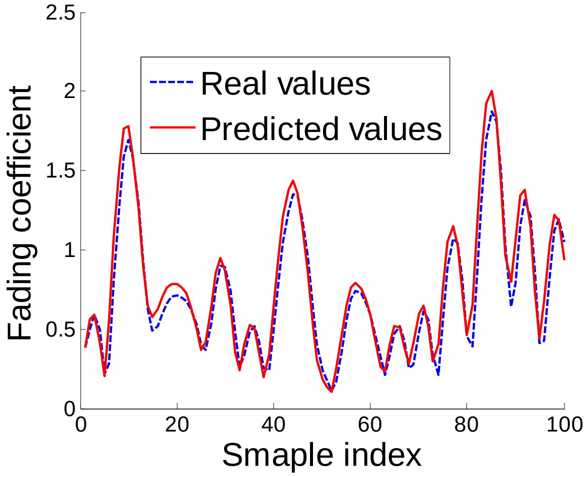

Fig. 2.3 Prediction capability of Wiener filtering with Doppler frequency of 100Hz (about speed of 54 km/hr) and parameter setting in section IV.

IV. NUMERICAL RESULTS

In this section, we use MATLAB simulation to compare the channel-prediction algorithms in terms of received SNR. Then, we study the impacts of the prediction algorithms on the PF performance in terms of (block) error rate (BLER) and packet delay. We also include the ideal predictor, in which the scheduler uses the actual values of the instantaneous data rate for the future time slot to update the scheduling metrics and thereafter makes "prefect" scheduling decisions, to reveal the upper performance limit for the improvement of channel predictions.

Specifically, we use MATLAB to simulate a CDMA system consisting of a base station and 10 mobile terminals (users). Carrier frequency of 2 GHz is assumed. Jakes model [11] with AWGN provided by MATLAB is adopted to simulate the Rayleigh fast fading channel with a unique random seed for each user's channel. The system is using Binary DPSK modulation to avoid the need for a coherent reference signal at the receiver [4]. Like the W-CDMA systems, each time slot is 666 μs. (A typical TCP segment of 576 bytes is carried by two 10 ms frames or equivalently 30 slots [7].) At the beginning of each time slot, the base station assigns the slot to transmit data to one of the terminals in the system according to the PF scheduler and the channel-prediction algorithm in use. A simple ARQ algorithm is used where the re-transmissions of data blocks (one for each slot) have the highest priority over all first block transmissions, which are scheduled according to the PF scheduler. That is, once data in a time slot is received in error, re-transmission of the data block takes place immediately in the next slot regardless of the channel conditions.

Fig. 4.1 compares the received SNR averaged over all users for the extrapolation (Extr.), exponential-smoothing (Expo.) and Wiener-filtering (Wiener) methods. Two sets of results are presented in the figure, which correspond to the time-average SNR for the AWGN channel for each user being 15 and 7.5 dB, respectively. Since the PF scheduler tends to serve users with high instantaneous channel quality, the received SNR for users scheduled for service can be significantly higher than the time-average SNR for the associated AWGN channel. The difference between the received and the time-average SNR is commonly referred to as the scheduling gain. Fig. 4.1 confirms that the scheduling gain for the PF scheduler is large, if the channel-quality predictions are sufficiently accurate. It is also noticeable that the performance of Wiener-filtering method is always better than that of exponential-smoothing or extrapolation. When the feedback delay equals d=4 (time) slots, the Wiener filtering can even provide a nontrivial SNR gain of 4dB over the extrapolation and exponential-smoothing methods. Moreover, with $d \geq 3$, it is important to observe that the received SNR based on the extrapolation and exponential-smoothing are even lower than the time-average SNR of the user channel. Such implies that the PF scheduler with *unsatisfactory channel predictions* (e.g., by the commonly used extrapolation and exponential-smoothing methods) can perform even poorer than any random schedulers such as the round-robin algorithm.

Indeed, enhanced channel predictions certainly help reduce block error rate (BLER), as shown in Fig. 4.2. This is a natural consequence of the fact that accurate channel predictions enable the PF scheduler to make correct decision, thus improving the received SNR for the users selected for service. The figure shows that the BLER performance provided by Wiener-filtering predictions is much superior to those by the other two simple prediction algorithms in the whole parameter range of interest. More significantly, the Wiener filtering method can provide satisfactory BLER (say 0.01), while the other two methods cannot. This can be seen from the case with the time-average SNR of 15 dB for the feedback delay *d* larger than 1 time slot.

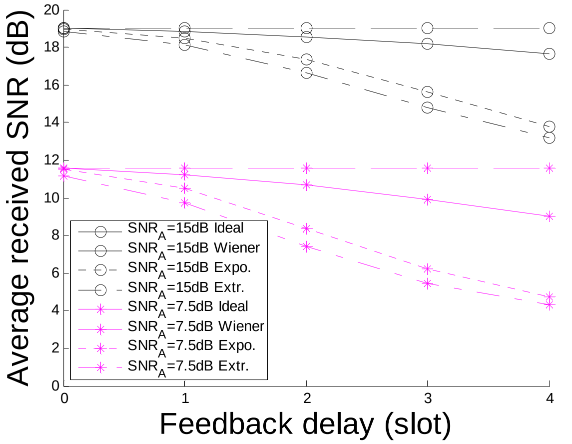

Fig. 4.1 Average received SNR (dB) with various feedback delay and velocity of 100 km/hr.

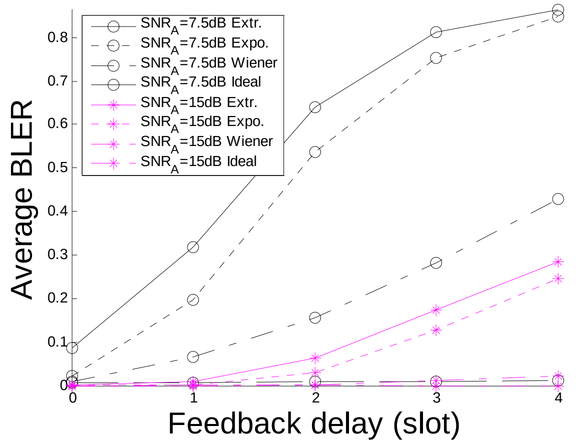

Fig 4.2 Average BLER versus feedback delay at velocity of 100 km/hr.

In Fig. 4.3 we show a comparison of packet delay performance between the packet schedulers with different channel predictions. The packet delay here is defined as the delay from the time when a packet enters the scheduling queue until the moment when the packet is received successfully. Significant differences in packet delay among the prediction algorithms are observed. As evident in the figure, a large reduction in packet delay from the enhanced channel predictions are observed when the time-average SNR is low. It is understandable because at the low SNR, packets are likely to be in error and subject to additional retransmissions, which can be avoided by adopting schedulers with accurate channel predictions.

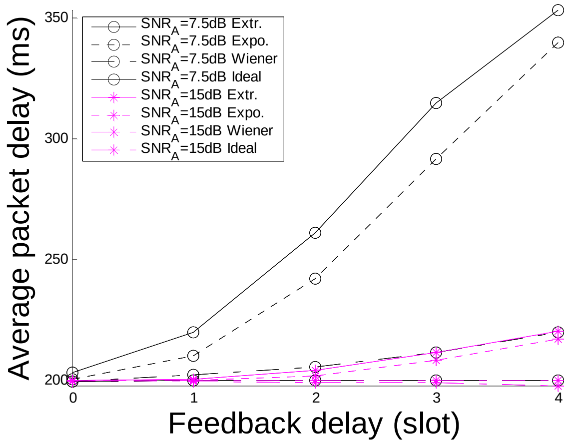

Fig 4.3 Average packet delay versus feedback delay at velocity of 100 km/hr.

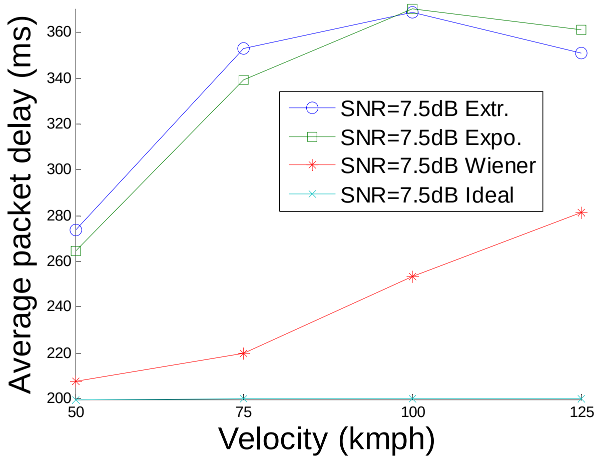

Fig 4.4 Average packet delay versus user velocity with feedback delay of 4 time slots.

We show a comparison between the current methods and the proposed one in terms of packet delay as a function of user velocity in Fig. 4.4. A general observation from these results is that inaccurate channel predications by the extrapolation and exponential-smoothing methods result in frequent retransmissions, thus unnecessary increasing packet delay, when compared with that of the Wiener filtering method. Even for the velocity at 125 km/hr, which is a fairly high vehicular speed in practical communication systems, the Wiener filtering method can still provide a delay improvement of more than 20% over the other two methods. Having said this, the latter method will eventually break down for excessive velocity simply because the Wiener filter will not be adequate for predicting highly varying channel at very high speed. This will remain an open issue for our future study.

V. CONCLUSIONS

In this paper, we have demonstrated and quantified how the inaccuracy of predicted data rates in future time slots for various users can significantly degrade the performance of the PF scheduling in wireless networks. We have proposed to enhance the scheduling algorithm by using an appropriate algorithm to improve the accuracy of the data-rate predictions. In particular, the Wiener filtering technique can be applied to accurately predict data rates for Rayleigh fading channels. Our simulation results reveal that relatively to the commonly used extrapolation and exponential-smoothing methods, the channel predictions by the Wiener filter noticeably improves the PF scheduler's performance in terms of users' received SNR, error rate and packet delay.

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