IMPROVING MINIMUM RATE MAXIMIZATION LINK ADAPTATION STRATEGY USING CHANNEL PREDICTION

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ABSTRACT

Minimum Rate Maximization (MRM) is a link adaptation strategy that guarantees a minimum quality of service, in terms of instantaneous signal-to-interference-plus-noise ratio, to all users in a DS-CDMA system. This is achieved by power and rate allocation that maximizes the minimum user information rate. As MRM resource allocation relies on knowledge of the channel coefficients, the achievable quality of service suffers from a degradation when the channel is dynamic and imperfectly estimated. The purpose of this paper is to add Auto-Regressive channel prediction to compensate for the Doppler-induced channel time-variations and improve the performance of the MRM strategy.

1. INTRODUCTION

Link adaptation is intended to improve communication systems' performance by adapting the different parameters, such as powers, rates, modulation type, frame length, to the dynamic channel and to the specific constraints of the target application. In the context of emerging third generation (3G) standards, such as the DS-CDMA-based UMTS [1], much work is devoted to link adaptation. With regard to the optimization goal, different approaches do exist [2-4]. Most of these strategies, such as the one proposed in [2], were interested in total throughput maximization. The drawback of this approach is that it favors the strong users, who experiment good propagation conditions, while those suffering from deep fades are prohibited from transmitting until their fading becomes less severe. Thus, no minimum quality of service is guaranteed. The resulting latency cannot be tolerated in real-time applications.

A "fairer" approach is the MRM (Minimum Rate Maximization) strategy proposed in [5]. Its objective is to guarantee a minimum quality of service, in terms of Signal-to-Interference-plus-Noise Ratio (SINR), to all users. This is achieved by allocating powers and rates that maximize the minimum user rate for each frame. The solution to this optimization problem was derived assuming a static known channel. When the channel taps are unknown and time-varying, the only available information to the base station is their estimates. The effect of this imperfect channel knowledge on MRM performance has been studied in [6] where we showed that the achievable minimum SINR's suffers from some degradation due to channel estimation errors and Doppler spread. Therefore, the present work proposes to use channel prediction in order to compensate for the Doppler effect and enhance the average performance. Simulations substantiate the expected improvement in system robustness.

2. SYSTEM MODEL

Consider an uplink in a DS-CDMA system with one cell containing N_u mobile users. The multi-path fading channel is frequency-selective with L resolvable paths. Each resolvable path l is characterized by its complex gain g_l^k and path delay τ_l^k. We suppose that g_l^k and τ_l^k vary slowly enough to be considered as invariant during a single frame. Thus, we use the frame index n as a time label. In the *Wide-Sense Stationary Uncorrelated Scattering* (WSSUS) reference model [7], each g_l^k is a zero-mean complex circular gaussian random process of variance $\sigma^2 = \frac{1}{2}E\left[|g_l^k|^2\right]$ per component.

At the base station, an *L-finger Rake Receiver* for each user is assumed. The *Multiple-Access Interference* at the receiver output is modeled as a complex additive white gaussian noise which is independent of the thermal white gaussian noise of power spectral density N_0. Therefore, during the nth frame, the SINR $\gamma_k(n)$ for the kth user is given in [8] as follows

$$\gamma_k(n) = (r_k(n))^{-1}\frac{a_k(n)P_k(n)}{N_0 + \beta\sum_{j\neq k} a_j(n)P_j(n)} \qquad (1)$$

where $r_k(n)$ and $P_k(n)$ are the allocated instantaneous information rate and transmission power respectively, $a_k(n)$ is the channel power gain and β is a spreading-sequence dependent constant ($\beta = 2/3$ typically [8]). The channel power gain is

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[*] The third author participated in this work while he was visiting ETIS and other laboratories in France on a Fulbright Grant.

defined by

$$a_k(n) = \sum_{l=1}^{L} \left|g_l^k(n)\right|^2$$

In practice, where only estimates $\hat{g}_l^k$ of the g_l^k are available to the base station, an estimated power gain is given by

$$\hat{a}_k(n) = \sum_{l=1}^{L} \left|\hat{g}_l^k(n)\right|^2$$

with $\hat{g}_l^k(n) = g_l^k(n) + e_l^k(n)$ where e_l^k is the estimation error which is independent of g_l^k and modeled here by a zero-mean complex white gaussian noise with variance σ_e^2 per component. We define the *channel estimation error relative variance* by $e = \sigma_e^2/\sigma^2$. This ratio is used as a metric for the channel estimation accuracy.

In the simulations, the coefficients g_l^k are generated using a modified version of the *Jake's model* proposed in [9]. With $M = 8$, a typically chosen value for the number of the underlying sinusoidal oscillators, the obtained statistical properties match well those of the reference WSSUS model.

Since we assume that the channel is slowly-fading with respect to the frame duration T_f, the *Doppler Spread* f_d must satisfy the inequality $f_d T_f \ll 1$. We choose a maximum normalized Doppler shift of $f_d T_f$=0.1. In UMTS, where T_f is constant and equal to 10 ms [1], this choice leads to f_d=10 Hz. With a standard UMTS carrier frequency of about 2 GHz, this Doppler shift corresponds to a pedestrian environment with a speed of 5 km/h.

3. MRM BASICS

The goal of MRM is to find rates $r_k(n)$ and powers $P_k(n)$ that maximize the instantaneous minimum user information rate $r_{min}(n) = min\{r_k(n), k = 1,..,N_u\}$ assuming that a minimum quality of service, in terms of a target SINR γ_t, is guaranteed to all users [5]

$$\gamma_k(n) = \gamma_t,\ k = 1,..,N_u \tag{2}$$

According to (1) and (2), we have

$$r_k(n) = \gamma_t^{-1} \frac{a_k(n)P_k(n)}{N_0 + \beta \sum_{j \neq k} a_j(n)P_j(n)} \tag{3}$$

The solution to this optimization problem has been derived in [5] under the assumption that the channel gains $a_k(n)$ are a priori known to the base station. In this case, the maximized minimum rate $max(r_{min})$, denoted by $r(n)$, is given by

$$r(n) = \gamma_t^{-1} \frac{a_{min}(n)P_m}{N_0 + \beta(N_u - 1)a_{min}(n)P_m} \tag{4}$$

where P_m is the maximum allowed transmission power and $a_{min}(n) = min\{a_k(n), k = 1,..,N_u\}$ is the minimum power gain, corresponding to the weakest user during the nth frame. This solution corresponds to the following power allocation

$$P_k(n) = \frac{a_{min}(n)}{a_k(n)} P_m \tag{5}$$

Inserting $P_k(n)$ from (5) into (3), allows us to conclude that the allocated rates have r as a common value, i.e $r_k(n) = r(n)$ for $k = 1,..,N_u$.

In practice, the base station does not know the value that the channel power gain $a_k(n)$ will take during the next frame of index n. One possible solution is to use the channel state estimated during the previous frame. In this case, the actual gain $a_k(n)$ is replaced by its previous estimate $\hat{a}_k(n-1)$. The impact of this choice on the allocated rates and the achieved SINR's depends on the channel estimation accuracy and on the Doppler spread. The resulting performance degradation was studied in [6] where we showed that the average minimum SINR falls below the target value γ_t. That is why we propose here to introduce channel prediction so that the unknown gain $a_k(n)$ can be replaced by its predicted value $\tilde{a}_k(n)$ instead of the previous estimate $\hat{a}_k(n-1)$.

4. PREDICTION-BASED MRM LINK ADAPTATION

After introducing the AR prediction, this section shows how link adaptation is modified when based on the predicted gain.

4.1. Auto-Regressive Channel Prediction

The prediction of the gain is performed in theory from its previous samples as follows

$$\tilde{a}_k(n) = \sum_{i=1}^{P} c_i\ a_k(n-i)$$

where P is the AR model order and c_i are its coefficients. Since the base station ignores the actual values of the gain previous samples $a_k(n-i)$, they are replaced by their estimates $\hat{a}_k(n-i)$. The coefficients c_i are obtained by resolving the *Normal Equations* where the autocorrelation function of a_k is replaced by an estimator based on a finite number of previous samples of $\hat{a}_k$. The prediction error is defined by $\epsilon_k(n) = \tilde{a}_k(n) - a_k(n)$. The AR model order P is chosen to guarantee low variance of ϵ_k but it has to remain reasonable for complexity considerations. By plotting the variance of ϵ_k versus P, we obtain the curves of Fig. 1 corresponding to different values of $f_d T_f$. Notice that beyond a given order there is no significant improvement in the prediction performance. As a result, we choose $P = 8$.

4.2. MRM with predicted gain

Now we examine how MRM resource allocation and achievable SINR's are affected when the predicted gain is used instead of its actual value. By replacing in (5) the actual gain

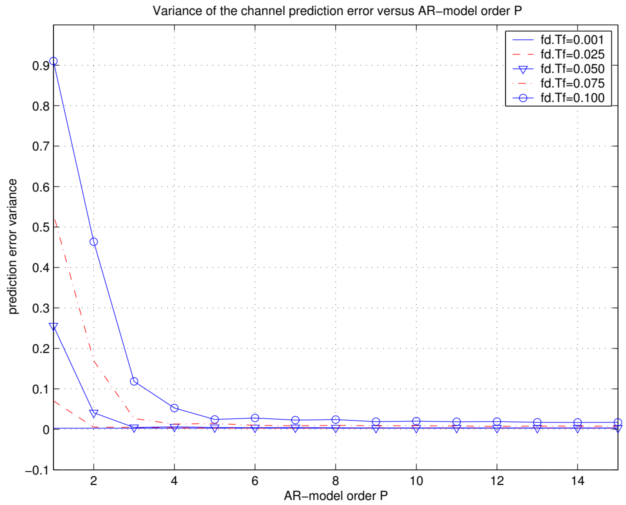

Fig. 1. Prediction error variance versus AR order P.

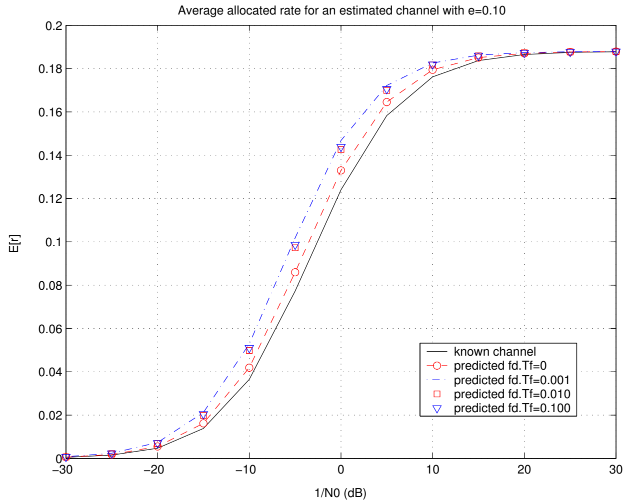

Fig. 2. Average rate for $e = 0.10$.

$a_k(n)$ by the predicted one $\tilde{a}_k(n)$, the power allocation becomes

$$\tilde{P}_k(n) = \frac{\tilde{a}_{min}(n)}{\tilde{a}_k(n)} P_{max} \tag{6}$$

with $\tilde{a}_{min}(n) = \min\{\tilde{a}_k(n), k = 1, .., N_u\}$. As the objective of MRM is to guarantee the same SINR to all users, the base station allocates the rates according to (3) as follows

$$\tilde{r}_k(n) = \gamma_t^{-1} \frac{\tilde{a}_k(n)\tilde{P}_k(n)}{N_0 + \beta \sum_{j \neq k} \tilde{a}_j(n)\tilde{P}_j(n)} \tag{7}$$

A *tilda* is added to the rates' symbols as they are a priori different from the ideal ones $r_k(n)$. Replacing powers $\tilde{P}_k(n)$ in (7) from (6) shows that the allocated rates continue to share a common value $\tilde{r}(n)$ as follows

$$\forall k,\ \tilde{r}_k(n) = \tilde{r}(n) = \gamma_t^{-1} \frac{\tilde{a}_{min}(n)P_m}{N_0 + \beta(N_u - 1)\tilde{a}_{min}(n)P_m} \tag{8}$$

4.3. Prediction-based SINR's

Using the predicted gain, we saw that the base station chooses powers and rates hoping that the SINR's on the different uplinks will be equal to the target value γ_t for the next frame. Unfortunately, it is not the case. This can be deduced from (1) when $P_k(n)$ are replaced by $\tilde{P}_k(n)$ and $r_k(n)$ are replaced by $\tilde{r}(n)$

$$\tilde{\gamma}_k(n) = (\tilde{r}(n))^{-1} \frac{a_k(n)\tilde{P}_k(n)}{N_0 + \beta \sum_{j \neq k} a_j(n)\tilde{P}_j(n)} \tag{9}$$

According to (6) and (8), equation (9) becomes

$$\tilde{\gamma}_k(n) = \gamma_t \frac{a_k(n)[N_0 + \beta(N_u - 1)\tilde{a}_{min}(n)P_m]}{\tilde{a}_k(n)[N_0 + \beta\tilde{a}_{min}(n)P_m \sum_{j \neq k} \frac{a_j(n)}{\tilde{a}_j(n)}]} \tag{10}$$

As the target of MRM strategy is to guarantee a minimum quality of service, we are interested in the minimum SINR over the different uplinks. Thus, after normalizing the SINR's to the target value γ_t, we define a *minimum normalized SINR* by $\tilde{\rho}_{min}(n) = \min\{\frac{\tilde{\gamma}_k(n)}{\gamma_t}, k = 1, .., N_u\}$.

5. SIMULATION RESULTS

The MRM performance is characterized here by the average allocated rate and the average minimum normalized SINR. As the only random parameter in (8) is the minimum predicted gain $\tilde{a}_{min}$, the average rate $E[\tilde{r}]$ depends on the probability density function (PDF) of $\tilde{a}_{min}$. Unfortunately, the complexity of deriving this PDF makes it difficult to get an analytical expression for $E[\tilde{r}]$. The expression of the instantaneous SINR $\tilde{\gamma}_k$, given by (10), is more complicated again since it involves three random parameters (a_k, $\tilde{a}_k$ and $\tilde{a}_{min}$). So, there is little hope to calculate the average minimum normalized SINR $E[\tilde{\rho}_{min}]$ analytically. However, simulation allows us to evaluate these averages versus the channel estimation error variance e and the normalized Doppler spread $f_d T_f$. The remaining parameters are chosen as follows: $N_u = 5$, $L = 3$, $P_m = 1$ and γ_t =3 dB.

Consider the case of an estimated channel with $e = 0.1$ for example. The curves of Fig. 2 show that the difference between $E[\tilde{r}]$ and $E[r]$ depends on the Doppler spread. This difference is due to the fact that the prediction is disturbed by the channel estimation errors affecting the observation at the predictor input. Notice that $E[r]$ is not an upper bound for the possible average rates. In fact, the base station is free to allocate instantaneous rates that exceed the one given by (4) but the constraint on the instantaneous SINR's, defined by (2), is no longer satisfied. So, if $E[\tilde{r}] \geq E[r]$, the price paid is a loss in the average minimum quality of service.

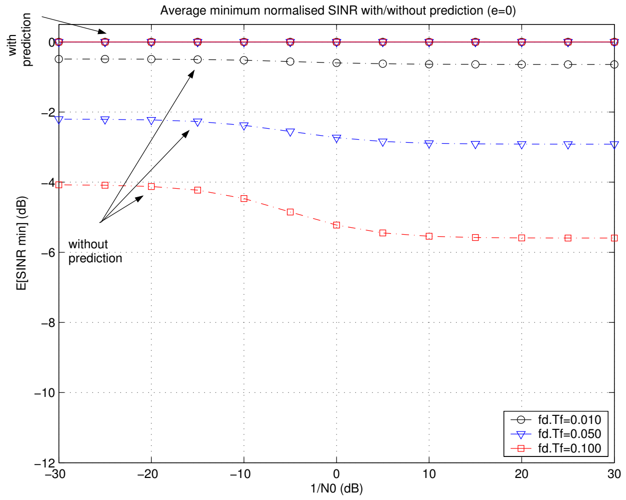

Fig. 3. Prediction-improved average minimum normalized SINR for $e = 0$.

To see how the channel prediction improves the robustness of the MRM strategy, we compare the prediction-based average minimum normalized SINR $E[\tilde{\rho}_{min}]$ with the simulation results that were presented in [6]. We showed in [6] that the average minimum normalized SINR, denoted $E[\rho_{min}]$, falls below the target value of 0 dB when powers and rates for the nth frame are allocated using the estimated gain $\hat{a}_k(n-1)$ during the previous frame.

Consider a dynamic ($f_dT_f > 0$) and perfectly estimated channel ($e = 0$). In Fig. 3, we plot the curves of $E[\rho_{min}]$ with those of $E[\tilde{\rho}_{min}]$ obtained with channel prediction. Notice that for all the considered values of f_dT_f, the prediction compensates for the minimum SINR degradation on average as all the solid-line curves match the target line of 0 dB.

In Fig. 4, we add channel estimation errors and examine how the prediction improves the average minimum normalized SINR for $1/N_0$=10 dB. The difference $E[\tilde{\rho}_{min}] - E[\rho_{min}]$ is plotted as a function of the normalized Doppler spread f_dT_f for different values of e. We conclude that the prediction significantly improves the average performance in terms of minimum SINR. This improvement increases with f_dT_f. However, it remains limited by the channel estimation errors as, for a given f_dT_f, the effect of the prediction is less significant for high values of e.

6. CONCLUSION

In this paper we showed how AR channel prediction improves the robustness of the MRM link adaptation strategy. AR channel prediction compensates for the channel time-variations and helps guarantee the target minimum quality of service on average. This improvement remains limited by the channel estimation errors.

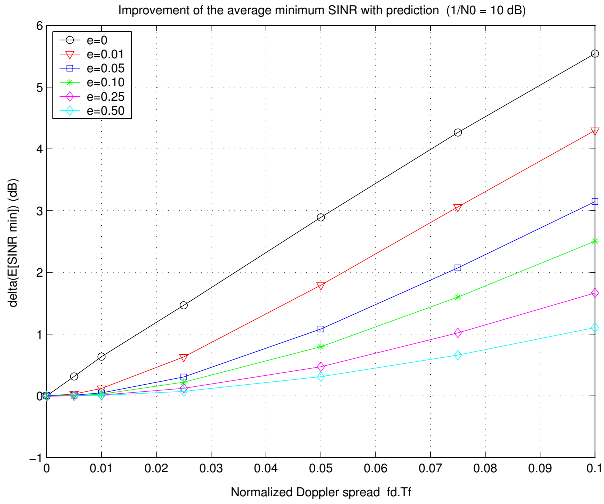

Fig. 4. Prediction-improved average minimum normalized SINR for $1/N_0$ =10 dB.

Future work will focus on taking into account the channel estimation errors' model in the MRM optimization problem.

7. REFERENCES

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