Resource Allocation for Data in Presence of Voice in Cellular CDMA with Correlated Interferers

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ABSTRACT
Allocation of processing gain for data users using variable processing gain (VSG) in presence of voice users in cellular direct sequence (DS)-CDMA is considered. Optimal processing gain for data is determined while maintaining voice QoS (quality of service) in terms of outage probability. Optimal processing gain for data is allocated satisfying a constraint on voice outage probability. Effects of voice users on optimal processing gain, throughput and delay of data users are investigated. The analysis is carried out considering the existence of correlation amongst signal and interferers and power control error (pce). The effects of correlation and pce on throughput, delay and optimal processing gain of data users have also been indicated.

Key words: Throughput, delay, correlated interference, pce.

I INTRODUCTION

Wireless networks are growing at a phenomenal rate to support multimedia services such as voice, data and video etc. These services will have different characteristics and quality requirements. Allocation of scarce resources such as bandwidth and power among the users will have a significant impact on system capacity. Resource allocation for wireless networks is an important issue and has been discussed considerably in the literature [1, 2].

CDMA is a promising access technique for supporting multimedia traffic with QoS in cellular wireless networks. In wireless networks there has been a rapid growth in demand for high data rate and quality of service. Thus Packet data transmission at high rate is becoming important in wideband CDMA. Data rate in DS-CDMA can be increased by using variable spreading gain (VSG) CDMA or multi-code (MC) CDMA. In VSG scheme, the data rate is determined by an appropriate selection of processing gain while additional parallel codes are allocated for increasing data rate in MC-CDMA.

The QoS in DS-CDMA can be controlled by an appropriate selection of transmission power and processing gain. Processing gain is varied by varying the symbol duration. Low processing gain which reduces packet transmission time by reducing symbol duration also decreases SINR (signal to interference noise ratio). The packet error rate increases which results in higher retransmission probability. As the processing gain (pg) increases, packet error rate reduces which tends to reduce the average delay. However increasing processing gain also increases the symbol duration; so there is a trade off between the decrease in average delay (D) caused by decrease in packet error and increase in D caused by increase in symbol duration.

The assignments of transmit power and processing gain for two classes of voice and data in cellular CDMA is considered in [1]. The effects of this assignment on throughput and delay performance of data have been shown in [1] which assumes perfect power control in a single cell. However in practice, power control in cellular CDMA is imperfect [3,4]. The received power becomes lognormally distributed. In a practical situation the signal and interference shadowed by the same obstacle tend to be correlated [3,4]. Thus correlation can exist between any pair of interfering components as well as between signal and any interfering component. The correlation has a strong impact on BER (bit error rate) and hence on packet error of data [4, 6]. Allocation of processing gain for single class of data users is considered in [6] where the effects of correlation and pce on processing gain allocation are shown. However no optimal allocation of processing gain for data is considered in [6].

In the present paper we analytically study the allocation of processing gain for data users in presence of voice in cellular DS-CDMA considering imperfect power control and out-cell interference. We derive the optimal processing gain for data and show the influence of voice on such optimal conditions while maintaining a voice QoS based on an outage criterion. We investigate the effects of signal correlation and pce on optimal processing gain, throughput and delay of data. In section II we present the system model and analysis. Results and discussion are presented in section III. Finally we conclude in section IV.

II SYSTEM MODEL

A hexagonal cellular layout with three sectors per cell supporting equal number of voice (N_v) and data (N_d) users per sector is considered as in [5]. A voice
user transmits at a fixed rate on a single code depending on its processing gain (\(P_{g\text{v}}\)). The data user transmits on a single code at a variable rate \(R_{\text{d}}\) depending on the processing gain (\(P_{gd}\)). The processing gain of all codes allocated to data users are equal and is given as \(P_{gy} = W / R_{\text{d}}\); \(W\) is the spread bandwidth. A traffic model as in [1] is considered for both voice and data where each user generates a sequence of fixed length packet. A new packet is generated as soon as the preceding packet is delivered successfully. The number of active users is constant. This model is referred to as “continuously active” model [1] since the users transmit packet continuously. Voice traffic is assumed to be generated in the same manner as data. The packets are transmitted at symbol rate i.e. \(R_{c} / P_{gy}\) and \(R_{c} / P_{gd}\) for voice and data users respectively, where \(R_{c}\) is the chip rate. Error detection and retransmission are assumed to provide reliable data transmission using ARQ. However, erroneous voice packets are not retransmitted. There is no queuing delay for voice and data packets as per “continuously active” model. Let \(\lambda_{s}\) denotes the rate of arrival of voice packets and \(T_{p}\) denotes the packet transfer time. For voice, packet transfer time is same as transmission time \((T_{i})\) of a single packet where \(T_{i} = LP_{gy} / R_{c} \cdot L\) is the packet length. Thus maximum allowed processing gain for voice [1] \(P_{gy}^{v} = [R_{c} / \lambda_{s} \cdot L]\) where \([x]\) denotes the largest integer less than or equal x. The received signal and interference are considered as lognormal random variables (r.v.s) for an imperfect power controlled CDMA.

Let \(S_{i}\) be the required received power level at a reference base station (BS), where \(S_{i} = S_{t}(s_{0})\) depending on voice (data) user. The actual received signal at the BS is expressed as

\[
U = S_{i}e^{S}\quad (1)
\]

and overall interference as \(I = S_{i}e^{R}\quad (2)\)

where \(S\) and \(R\) are gaussian r.v.-s with mean \(m_{s}\), \(m_{R}\) and variances \(\sigma_{s}^{2}\), \(\sigma_{R}^{2}\) respectively. Expressing \(S_{s}\) in dB we have \(\sigma = \sigma_{s} / \beta\), where \(\beta=\ln(10)/10\) and \(\sigma\) is the power control error (pce) in dB. Assuming an ideal correlation receiver, the outage probability for voice is defined as

\[
P_{\text{out,v}} = P((U / I)_{P_{gy}} < \gamma) = P((S-R) < \gamma_{o})\quad (3)
\]

where \(\gamma_{o} = \log(\gamma / P_{gy})\), \(\gamma\) is the threshold in SIR to maintain the QoS. Let \(\varphi = S - R\), where \(\varphi\) is also a Gaussian r.v. with mean \(m_{\varphi}\) and variance \(\sigma_{\varphi}^{2}\). Now \(m_{\varphi} = m_{s} - m_{R}\) and \(\sigma_{\varphi}^{2} = \sigma_{s}^{2} + \sigma_{R}^{2} - 2 \cdot r_{SR} \cdot \sigma_{S} \cdot \sigma_{R}\)

where \(r_{SR}\) is the overall correlation coefficient between \(S\) and \(R\). The outage probability for voice \(P_{\text{out,v}}\) can now be expressed as

\[
P_{\text{out,v}} = P[\varphi < \gamma_{o}] = 1 - Q(\gamma_{o} - (m_{s} - m_{R}) / \sqrt{\sigma_{S}^{2} + \sigma_{R}^{2} - 2 r_{SR} \cdot \sigma_{S} \cdot \sigma_{R}})\quad (5)
\]

We determine the mean (**m** \(_{R}\)) and variance (**\(\sigma_{R}^{2}\)) of the resultant lognormal interferer considering a correlation ‘\(r\)’ between any pair of interferers. For a reference voice user the in-cell interference consists of \(N_{v}+N_{d}\) terms and the out-cell interference consists of \(N_{v}+N_{d}\) terms [5]. We assume \(S_{v} = S_{d} = S_{R}\) and consider the following two r.v.s \((u_{1}, u_{2})\) used to evaluate \(m_{R}\) and \(\sigma_{R}\)

\[
u_{1} = \frac{E[I]}{S_{0}} = E[e^{R}] = m_{R} + \frac{\sigma_{R}^{2}}{2}
\]

\[
u_{2} = \frac{E[I^{2}]}{S_{0}^{2}} = E[e^{2R}] = m_{R}^{2} + 2 \sigma_{R}^{2}
\]

and

\[
u_{1} = \sum_{i=1}^{t_{1}} m_{y_{i}} + 0.5 \sigma_{y_{i}}^{2} + \sum_{j=1}^{t_{2}} m_{y_{j}} + 0.5 \sigma_{y_{j}}^{2}
\]

\[
u_{2} = \sum_{i=1}^{t_{1}} 2 m_{y_{i}} + 2 \sigma_{y_{i}}^{2} + \sum_{j=1}^{t_{2}} 2 m_{y_{j}} + 2 \sigma_{y_{j}}^{2}
\]

\[
u_{1} = \sum_{i=1}^{t_{1}} \sum_{j=i+1}^{t_{2}} m_{y_{i}} + m_{y_{j}} + 0.5 \sigma_{y_{i}}^{2} + 0.5 \sigma_{y_{j}}^{2} + 2 r_{jk} \sigma_{y_{i}} \sigma_{y_{j}}
\]

\[
u_{2} = \sum_{i=1}^{t_{1}} \sum_{j=i+1}^{t_{2}} 2 m_{y_{i}} + m_{y_{j}} + 0.5 \sigma_{y_{i}}^{2} + 0.5 \sigma_{y_{j}}^{2} + 2 r_{jk} \sigma_{y_{i}} \sigma_{y_{j}}
\]

Here \(m_{y_{i}}, m_{y_{j}}, m_{y_{k}}\) are means and \(\sigma_{y_{i}}, \sigma_{y_{j}}, \sigma_{y_{k}}\) are standard deviations of the i-th, j-th and k-th lognormal components respectively: \(r_{ik}, r_{jk}, r_{ij}\) are the pair wise correlation between them and \(t_{1} = 2N_{v} - 1, t_{2} = 2N_{d}\). For identical lognormal components with same correlation coefficients among all the components, let \(m_{y_{i}} = m_{y_{j}} = m_{y_{k}} = m_{y}\), \(\sigma_{y_{i}} = \sigma_{y_{j}} = \sigma_{y_{k}} = \sigma_{y}\) and \(r_{ik} = r_{jk} = r_{ij} = r\) for all i, j and k. Further \(m_{y} = m_{s}\), \(\sigma_{y} = \sigma_{s}\) are assumed. Solving equations (8) and (9) we get

\[
\sigma_{R}^{2} = \ln(u_{2}) - 2 \ln(u_{1})
\]

The overall correlation coefficient \(r_{SR}\) between the signal and interference is evaluated as [4]

\[
r_{SR} = \frac{2[\ln(v) - (m_{s} + m_{R})] - (\sigma_{s}^{2} + \sigma_{R}^{2})}{2 \sigma_{S} \sigma_{R}}
\]

where \(v = E[e^{S} e^{R}]\)

\[
t_{1} = \sum_{i=1}^{t_{1}} m_{y_{i}} + m_{y} \cdot \frac{1}{2} \sigma_{y_{i}}^{2} + r_{y_{i}} \sigma_{y_{i}} \sigma_{y_{j}}
\]

\[
t_{2} = \sum_{j=i+1}^{t_{2}} m_{y_{j}} + m_{y} \cdot \frac{1}{2} \sigma_{y_{i}}^{2} + r_{y_{i}} \sigma_{y_{i}} \sigma_{y_{j}}
\]

\[
\sum_{j=i+1}^{t_{2}} m_{y_{i}} + m_{y} \cdot \frac{1}{2} \sigma_{y_{i}}^{2} + r_{y_{i}} \sigma_{y_{i}} \sigma_{y_{j}}
\]

\[
(13)
\]
and \( r_{sy} = r \)

Now for a fixed number of data users \( N_d \), one can estimate the maximum number of voice users \( N_v = N_{v_{\max}} \) so as to satisfy \((P_{out} < \delta)\) using eqn (5) to (13).

**BER for data**

When the desired user is a data user, \( t_1 \) and \( t_2 \) in eqns (8, 9, 13) are modified as \( t_1 = 2N_v \) and \( t_2 = 2N_v - 1 \). With this modification we follow the earlier steps developed to evaluate \( m_R \) and \( \sigma_R \) and \( r_{SR} \). The BER of data is [6],

\[
P_e = \frac{2}{3}Q(e^{mk}) + \frac{1}{6}Q(e^{mk+\sqrt{5}\sigma k}) + \frac{1}{6}Q(e^{mk-\sqrt{5}\sigma k})
\]

where \( m_k = \frac{1}{2}(\ln(2P_{gd}) + m_s - m_R) \)

\[
\sigma_k^2 = \frac{1}{4}(\sigma_s^2 + \sigma_R^2 - 2r_{SR}\sigma_s\sigma_R)
\]

**Delay and Throughput Analysis**

The retransmission probability \( P_r \) is given as

\[
P_r = 1 - (1 - P_e)^{L/c}
\]

where \( L \) is the length of the packet in bits and \( r_c \) is the FEC code rate. \( P_e \) is the channel BER as derived in (14). For continuously active data users, there is no waiting delay in the queue. So the average packet delay is the same as the packet transfer time \( T_p \). The time required for transmitting a packet of length \( L \) by a data user transmitting at a rate of \( R_b \) is:

\[
T_i = \frac{L}{R_b} = \frac{L}{P_{gd}R_c}
\]

Assuming a packet is received successfully at 'k' th transmission attempt, preceded by '(k-1)' retransmission, the transfer time of a single packet \( \psi \) is geometrically distributed [6].

\[
P}\{\psi = kT_i\} = P_r^{k-1}(1 - P_r)
\]

Where \( k = 0, 1, 2, \ldots \), and \( P_r \) is the retransmission probability. The average packet transfer time is

\[
T_p = E[\psi] = \frac{T_i}{(1 - P_r)} = \frac{L}{R_c(1 - P_r)} P_{gd}
\]

The average delay \( D = T_p = \frac{L}{R_c(1 - P_r)} P_{gd} \)

The average throughput (G) is defined as the average number of information bits successfully transferred per sec and is given as

\[
G = \frac{Lr_cP_{gd}}{D} = \frac{r_cR_c(1 - P_r)}{P_{gd}}
\]

In order to determine the optimum processing gain \( P_{gd}^* \) we put the condition \( d(G)/dP_{gd} = 0 \) and \( P_{gd}^* \) is obtained by solving the following differential equation:

\[
\frac{Lr_cP_{gd}}{(1 - P_e)} \frac{dP_e}{dP_{gd}} + 1 = 0
\]

\( P_e \) is a function of \( P_{gd}^* \) via eqn (14) and also includes correlation \( r_{SR} \). For a given \((N_v, N_d)\) pair, \( P_{gd}^* \) can be determined. Maximum throughput and minimum delay is obtained by substituting \( P_{gd} = P_{gd}^* \) in eqns (20,21). Now we present analytical results to indicate the effects of correlation and pce on \( P_{gd}^* \), optimum G and D.

**IV RESULTS AND DISCUSSION**

The following parameters are assumed. The spread bandwidth \( W = 5.0 \) MHz, chip rate \( R_c = 5 \) Mchips/sec, packet length \( L = 768 \) and channel code rate \( r_c = 0.5 \). Two values of pce are considered \( \sigma = 1.0 \) dB, 1.5 dB, \( \gamma = 7 \) dB, \( \lambda_v = 14.4 \) kbps corresponds to arrival rate of 18.75 voice packets per sec, \( P_{out \_v} < \delta \) where \( \delta = 10 \% \). With the above parameters, the allocated processing gain to voice users is found as \( P_{gd}^* = 347 \). For \( N_d = 5 \) users/sector, \( N_{v_{\max}} \) satisfying \((P_{out \_v} < \delta)\) is found as \( N_{v_{\max}} = 23 \) for \( r = 0 \) and pce = 1.0 dB. For allocating resource to data users we consider \( N_v \) limited to 20 in present case.

Fig.1 shows the maximum throughput of data at optimum processing gain vs voice users for two values of \( N_d = 2 \) and 5. Throughput due to optimal processing gain is also compared with that of a fixed processing gain scheme of \( P_{gd} = 200 \) and 150. Data throughput decreases with increase in voice interference. Optimal processing gain is found to significantly improve the data throughput as compared to a fixed processing gain [curve (i,ii), (iii, iv and v)].

Fig.2 shows the delay of data users due to optimal processing gain vs voice users for \( N_d = 2 \) and 5. Optimal processing gain yields lower delay than a fixed processing gain scheme. Further it is observed that while optimal processing gain yields almost a linear increase in delay, fixed processing gain \( (P_{gd} = 200,150) \) increases delay abruptly with increase in voice users [curve (i, iii, iv, v)].

Fig.3 shows the optimal packet retransmission probability of data users \( (P_r) \) vs voice users for two values of correlation \( r = 0, 0.5 \) and pce 1.0 dB and 1.5dB. It has been shown in [4,6] that higher correlation as well as lower pce reduces BER (bit error rate) and packet retransmission probability. Hence higher correlation and lower pce improve the throughput and delay performance of data users in [6]. Here also we observe that a higher correlation of \( r = 0.5 \) reduces \( P_r \) as compared to \( r = 0 \) while other conditions remain identical (curve ii,iii). A higher pce of 1.5 dB increases the packet error and hence retransmission probability [curve (i,ii)].
Fig. 4 shows optimal processing gain of data vs voice users for r=0, 0.5 and pce =1.0 dB and 1.5 dB. With increase in number of voice user, optimal processing gain required for data user increases. Higher signal correlation lowers optimal processing gain while higher pce increases optimal processing gain [curve (ii,iii),(i,ii)].

Effects of correlation and pce on maximum throughput are depicted in Fig. 5. As higher correlation reduces packet retransmission and optimal processing gain, higher throughput is obtained for a correlation r=0.5 compared to r=0 [curve (i, ii)]. Higher pce increases retransmission probability and optimum processing gain; thus results in lower throughput as compared to pce =1.0 dB [curve (ii, iii)].

Fig. 6 depicts the effects of correlation and pce on data delay. Higher correlation (r=0.5) increases optimal throughput, it reduces delay at optimal processing gain as compared to r=0 [curve(ii, iii)]. A higher pce =1.5 dB which reduces optimal throughput results in increased delay as compared to a pce = 1.0 dB [curve (i, ii)].

IV CONCLUSIONS

Allocation of processing gain for data users in presence of voice users is studied analytically in DS-CDMA while maintaining a QoS constraint on voice in terms of outage. Effect of voice users on optimal processing gain is studied. Performances of data users improve significantly by optimal processing gain. Higher correlation reduces optimal processing gain and packet retransmission, thereby increases throughput and reduces delay. On the other hand, higher pce reduces throughput and increases delay at optimal processing gain as optimal processing gain and packet retransmission are increased for higher pce. Thus correlation and pce have significant effect in selecting optimal processing gain and data user’s performance.

REFERENCES

Fig. 3 Retransmission probability vs voice user at optimum processing gain of data users and $N_d = 5$.  
(i) pce = 1.5 dB, r=0  
(ii) pce = 1.0 dB, r=0  
(iii) pce = 1.0 dB , r=0.5

Fig. 4 Optimal processing gain of data vs voice, $N_d = 5$.  
(i) pce = 1.5 dB, r=0  
(ii) pce = 1.0 dB, r=0  
(iii) pce = 1.0 dB , r=0.5

Fig. 5 Maximum throughput of data vs voice user, $N_d = 5$.  
(i) pce = 1.0 dB r=0.5, (ii) pce = 1.0 dB, r=0  
(iii) pce = 1.5 dB, r=0.

Fig. 6 Delay of data at optimum processing gain vs voice users, $N_d=5$.  
(i) pce = 1.5 dB, r=0  
(ii) pce = 1.0 dB, r=0  
(iii) pce = 1.0 dB, r=0.5