A Reverse Link Outer-Loop Power Control Algorithm for cdma2000 1xEV Systems
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Abstract— Reverse Link Outer-Loop Power Control (ROLPC) algorithms developed for voice systems operate based on a continuous stream of packets (CRC events) to adjust the Power Control setpoint. Due to burstiness of data traffic a mechanism to distinguish between idle periods and data transmissions is necessary in systems optimized for data communications. In addition, such algorithms are unable to track changes in channel conditions during long idle periods. The proposed algorithm is designed to conservatively adapt to the channel in the absence of packets, with fast convergence at the start of a transmission. A parameterized algorithm is described with analysis and simulation results to justify baseline parameters. The performance of the algorithm for continuous and bursty TCP/IP traffic is presented.

Index terms— cdma 2000, 1xEV, HDR, Reverse Link Outer Loop Power Control, ROLPC, CDMA, and High Data Rate Cellular systems.

1. INTRODUCTION

3GPP2 adopted [1] an evolutionary approach to the existing cdma2000 standard for wireless Internet services. The standard known as 1x evolution (1xEV) or IS-856 - optimized for data - is the next generation solution to the ever-growing demand for high-speed wireless Internet access.

The 1xEV Reverse Traffic channel, shown in Figure 1 consists of a Pilot channel, a Reverse Rate Indicator (RRI) channel, a Data Rate Control (DRC) channel, an Acknowledgement (ACK) channel, and a Data channel. The RRI channel indicates the Reverse Traffic channel data rate. The DRC channel is used by the Access Terminal (AT) to indicate to the access network (AN) the requested Forward Traffic channel data rate and the selected forward link serving sector. The ACK channel is used by the AT to inform the AN whether or not the physical layer packet transmitted on the Forward Traffic channel was received successfully.

When no physical layer packet is transmitted on the Reverse Traffic channel, the access terminal transmits the null (zero or no data) data rate RRI codeword on the RRI channel. The Pilot and RRI channels are transmitted on the in-phase channel. The above channels are orthogonally spread by Walsh functions of length 4, 8, or 16 and each Reverse Traffic channel is identified by a distinct user long code. A complete explanation of the 1xEV Reverse Link is beyond the scope of this paper. Further information can be found in [1,4].

The principal purpose of power control is to mitigate the near-far problem and combat fading in order to provide each desired signal with adequate quality (Signal-to-Interference-and-Noise-ratio) while minimizing interference to other signals. Typically, the power control process on the reverse link consists of three elements:

- Open-Loop estimation of the reverse link transmit power given the turn-around equation and an estimate of the forward link received power at the access terminal (AT) – Open Loop Power Control
- Closed-loop correction, provided by the AN, to the open-loop estimation - Reverse Link Closed-Loop Power Control (RCLPC)
- Outer-loop adjustment of the RCLPC setting based on reverse link packet error events after selection combining -- Reverse Link Outer-Loop Power Control (ROLPC).

Each AT estimates the total received power on the forward link of the assigned CDMA channel. Based on this measurement and a correction supplied by the AN, the AT adjusts its transmit power (to compensate for the estimated path loss) such that a predetermined received power level is achieved at the AN. For closed-loop corrections, the AT adjusts its transmit power in response to each valid power control command received on the forward link. In 1xEV, the...
AT adjusts its Pilot Power in response to the RCLPC (update rate = 600Hz). The power levels of the Data, DRC and ACK channels are adjusted relative to the Pilot Channel power based on relative channel gains determined by the network. The closed-loop correction attempts to maintain the received pilot signal-to-noise ratio (for each AT) at a level given by a Power Control Threshold (PCT), or setpoint, such that the desired packet error rate (PER) is maintained. As the channel conditions vary, the target PER (e.g. 1%) is achieved by dynamically adjusting the PCT.

Design considerations for an ROLPC algorithm for data communications systems are discussed in Section II. The proposed algorithm is described and analyzed in Section III. Interaction of the algorithm with higher layer protocols is shown in Section IV along with a justification for the baseline values of the relevant parameters.

II. ROLPC FOR DATA COMMUNICATIONS

Key issues in designing a ROLPC algorithm for a data communications system are:

- Traffic-to-Pilot channel power scaling as a function of reverse link data rate.
- Adjustment to PCT on receipt of a good/bad packet.
- Differentiation between data and null transmissions
- PCT update during null transmissions

A. PILOT CHANNEL POWER SCALING AS A FUNCTION OF DATA RATE

Table I: Nominal Data Channel Gain relative to Pilot for a 1xEV Reverse Link

<table>
<thead>
<tr>
<th>Data Rate (kbps)</th>
<th>RRI</th>
<th>Nominal Data Channel Gain wrt Pilot (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>-∞ (Data Channel Is Not Transmitted)</td>
</tr>
<tr>
<td>9.6</td>
<td>1</td>
<td>3.75</td>
</tr>
<tr>
<td>19.2</td>
<td>2</td>
<td>6.75</td>
</tr>
<tr>
<td>38.4</td>
<td>3</td>
<td>9.75</td>
</tr>
<tr>
<td>76.8</td>
<td>4</td>
<td>13.25</td>
</tr>
<tr>
<td>153.6</td>
<td>5</td>
<td>18.5</td>
</tr>
</tbody>
</table>

In 1xEV the Pilot Ec/Nt is adjusted across data rates by adjusting the traffic-to-pilot ratio (as shown in Table I) so that PCT is not a function of data rate, which allow transitions at frame-rate (26.66ms) across data rates. As can be seen in Figure 4, the Pilot Ec/Nt required to achieve the target PER is roughly the same for all data rates. However, the required Pilot Ec/Nt to achieve the target PER (1% in this case) is a function of the vehicle speed with an approximate range of 2dB. Therefore an ROLPC algorithm is required to dynamically adjust the Pilot Ec/Nt.

B. PCT ADJUSTMENT ON RECEIVING GOOD/BAD PACKETS

Adjustment to PCT on receiving a bad packet optimizes between minimizing interference to other users and run-length of errors. Higher concentration of burst errors on the reverse link may adversely impact acknowledgements to forward link packets and consequently forward link throughput. Adjustment to PCT on receiving GOOD/BAD packets is discussed in detail in the next section.

C. DIFFERENTIATION BETWEEN DATA AND NULL TRANSMISSIONS

If a receiver is unable to distinguish an erroneous data packet from a stoppage of transmission, the ROLPC algorithm increases the target pilot Ec/Nt when it should ignore the output of the decoder. If this error occurs, the target pilot Ec/Nt is increased unnecessarily and excess power is transmitted until the target pilot Ec/Nt decreases to its steady state value. In 1xEV, the RRI channel not only aids rate determination but also provides reliable detection of null (no) transmissions. The RRI Channel provides a low probability of miss and false alarm in non-handoff scenarios regardless of channel conditions. In a 2-way soft-handoff imbalance\(^1\) scenario the performance is somewhat degraded at the weaker of the two reverse links. However, since ROLPC operates at the BSC which provides selection diversity on the received links this has little impact on the ROLPC performance.

D. PCT UPDATE DURING NULL TRANSMISSIONS

When the AT does not transmit or receive data for a predetermined time interval (dormancy period e.g. 10sec), the air link resources allocated to that AT are torn down and reallocated to other active users. The PPP connection is retained to facilitate fast-connection setup. The dormant mode in 1xEV systems allows efficient utilization of scarce air-link resources. If an AT is idle for a period of time less than the dormancy period the ROLPC algorithm has no straightforward mechanism to determine and adapt to changes in the AT’s channel conditions since the last packet transmission. The DRC channel erasure rate, speed or multi-path profile could be used to estimate the channel conditions; however, these mechanisms require a high-volume of communication between the BSC and BTS which may require an increase in backhaul capacity. To simplify, we propose a conservative bias to the PCT in this state. The algorithm transitions to this state if no packets are received for \(T_{nd}\) seconds (e.g. \(T_{nd} = 0.5s\)).

\(^1\) Imbalance is a condition in soft-handoff when the serving sector (forward link) is not the power-controlling sector.
III. ROLPC ALGORITHM

We now review the design considerations for a ROLPC algorithm.

A. PCT RANGE

The Data, DRC and ACK channels (if transmitted) scale their power levels relative to the Pilot Channel given sufficient PA headroom at the AT, the ROLPC algorithm operates on the Pilot Ec/Nt. As seen in Figure 4, the required Pilot Ec/Nt to achieve a given target PER is a function of vehicle speed. The resulting range determines the nominal range of setpoints over which ROLPC operates.

B. INITIAL PCT

The initial PCT for an AT at the start of a connection or following the dormant mode is chosen so as to ensure that packets transmitted at 9.6 kbps (guaranteed minimum data rate and maximum data rate for the first packet at the start of a transmission) would be successfully decoded regardless of vehicle speed with a high probability (e.g. 99%). Since the reverse link data packets may contain acknowledgements to forward link packets, a low PER on the initial reverse link transmission ensures minimal impact to forward link physical layer throughput and smooth operation of the higher layer protocols like TCP that employ windowing and congestion-control mechanisms.

C. TARGET PER

A target PER of 1% is chosen on the Reverse Link. A lower PER would use excess capacity on the Reverse Link. A higher PER would potentially degrade performance of reverse link data/signaling messages. In addition a higher error rate on reverse link packets carrying higher-layer acknowledgements for forward link traffic would degrade forward link throughput and adversely affect system performance. Studies show that a target PER of 1% provides an excellent optimization.

D. ROLPC STATES

<table>
<thead>
<tr>
<th>State/Mode</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inactive</td>
<td>The AT is in dormant mode; hence no ROLPC</td>
</tr>
<tr>
<td>Normal</td>
<td>Normal reverse traffic channel activity</td>
</tr>
<tr>
<td>No Data</td>
<td>No reverse traffic channel activity and AT is not in dormant mode</td>
</tr>
<tr>
<td>Data Start</td>
<td>Packet received while in No Data state. “GOOD” packets result in a higher than normal decrease of PCT. “BAD” packets result in a transition to Normal state.</td>
</tr>
<tr>
<td>Ratchet</td>
<td>PCT is higher than average Pilot Ec/Nt. Since AT’s transmit power is insufficient PCT not adjusted due to “BAD” packets</td>
</tr>
</tbody>
</table>

The ROLPC algorithm calculates the Power Control Threshold (PCT) to be used for the RCLPC. The PCT is updated dynamically at the arrival rate of packets, to track changes in the AT’s reverse link channel conditions. A brief description of the ROLPC states is presented in Table III. Figure 5 shows typical temporal traces of the PCT. Changes to the PCT are a function of the quality of the reverse traffic channel packets and the state of the ROLPC algorithm. A

“BAD” packet is one that resulted in a “CRC fail” event generated by the decoder given a valid RRI detection. A “GOOD” packet is one that resulted in a “CRC pass” event generated by the decoder given a valid RRI detection. In the Figure 5, the letters on the time axis indicate the status of the received reverse link traffic channel frames: G - GOOD frame, B - BAD frame, N - No frame received during that time frame.

General operation in each state is as follows:

**Normal:** In this state the AT transmits data on the reverse link. The PCT is updated based on the status (GOOD/BAD) of the received frames. For each GOOD frame received, the PCT is lowered slightly. When a BAD frame is received, the threshold is increased substantially in response to deterioration in channel conditions. The ratio of the adjustment when a BAD frame is received to that when a GOOD frame is received determines the target PER. The basis of adjusting the PC Setpoint is thus detection of traffic channel errors.

PCT is not adjusted in frame ‘n+1’ if it was adjusted in frame “n” owing to a “BAD” packet and a “BAD” packet was received in frame ‘n+1’ also. This is done in order to avoid excessive increase in PCT in response to degradation in channel conditions and to allow the change in the PCT setpoint to have an effect. In case of CRC failures in successive frames PCT is updated on alternate frames.

Let, ‘T’ denote the current PCT, $P_{\text{min}}$ and $P_{\text{max}}$, the minimum and maximum PC setpoints respectively. In the Normal mode, when a “BAD” packet is received $T$ is adjusted as $T_{\text{new}} = \min(T_{\text{old}} + \Delta_{\text{bad,n}}, P_{\text{max}})$ and when a “GOOD” packet is received $T$ is adjusted as $T_{\text{new}} = \max(T_{\text{old}} - \Delta_{\text{good,n}}, P_{\text{min}})$, where $T_{\text{new}}$ and $T_{\text{old}}$ are the values of $T$ after and before the ROLPC update. $\Delta_{\text{good,n}}$ and $\Delta_{\text{bad,n}}$ are the adjustments to $T$ in the normal mode on receiving a “GOOD” or “BAD” packet. The nominal step size chosen is $\Delta_{\text{bad,n}} = 0.5 dB$ (see Section IV for justification) and $\Delta_{\text{good,n}} = P_T \cdot \Delta_{\text{bad,n}}$, where $P_T$ is the target PER.
1. Analysis

We denote \( P_e \) as the probability of receiving a packet in error given that a valid RRI is received, \( P_m \) as the probability of erasing or missing an RRI (if the RRI is erased the decoder does not attempt a decode), \( P_f \) as the probability of a valid RRI (non-null data rate) being detected when NULL rate RRI was transmitted and \( \alpha \) as the probability of a packet being received in a given frame. In Normal mode, steady state, \( \Delta_{\text{good},n} \cdot \alpha(1-P_m)P_e + (1-\alpha)P_f \) which gives \[ \frac{\Delta_{\text{bad},n}}{\Delta_{\text{good},n}} = \frac{\alpha(1-P_m)P_e + (1-\alpha)P_f}{\alpha(1-P_m)(1-P_e)} \] (1)

if \( \alpha = 1 \), packets are being received almost every frame, which may be the case in Normal mode and therefore, \( \Delta_{\text{bad},n} = \Delta_{\text{good},n} \cdot \frac{P_f}{P_e} \cdot \frac{1}{P_f} \). This is consistent with the proposed algorithm. The smallest value of \( \alpha = 1/(N_{\text{nd}}-1) \) is governed by the largest number of consecutive frames for which no data is received while not transitioning to the NO-DATA mode. This is acceptable as the false alarm rate on the RRI channel is an order of magnitude lower. If \( \alpha = 0 \), \( \frac{\Delta_{\text{bad},n}}{\Delta_{\text{good},n}} = \frac{P_f}{\alpha(1-P_m)} \). In this case PCT is driven by false-alarm events. A large setting for \( N_{\text{nd}} \) results in wasted reverse link capacity. Too small a value would result in the PCT being increased even though data was being sent on the reverse link fairly regularly. Since the forward link scheduler\(^2\) determines when an AT gets served on the forward link, \( N_{\text{nd}} \) must be chosen to allow a reasonable interval that ensures that the AT gets served.

No Data: The algorithm enters this state when the AT stops transmitting for \( N_{\text{nd}} \) frames (e.g., 20 frames) which is much shorter than the dormancy timeout \( T_d \). To compensate for possible deterioration in the AT’s reverse link and to improve the likelihood that packets at the start of a new transmission are successfully decoded (the start of a new transmission on the reverse link is likely to be an acknowledgement for a packet received by the AT on the forward link) PCT is increased gradually every frame. Two maxima are defined for the NO-DATA mode. A local maximum \( \Delta_{\text{nd}} \) defines the maximum increase in PCT allowed in the NO-DATA mode. The local maximum is a function of the PCT at which the AT transitioned to this mode; i.e. the PCT is increased gradually in steps \( \Delta_{\text{nd,step}} \), where \( \Delta_{\text{nd,step}} = \Delta_{\text{nd}} / M \), \( M \) being the number of frames required for \( \Delta_{\text{nd}} \) adjustment in PCT. The maximum increase is limited to \( \Delta_{\text{nd}} \) relative to the PCT when the AT entered this mode. The global maximum \( (\Delta_{\text{nd,\text{max}}}) \) is the absolute maximum PCT allowed in the NO-DATA mode. Without the global maximum the PCT would increase by the delta allowed when in NO-DATA mode for an intermittent transmission with packet interarrival period less than the dormancy timeout or due to false alarms; eventually reaching \( P_{\text{max}} \). If the PCT is higher than \( P_{\text{nd,\text{max}}} \) when the algorithm enters this state it is adjusted down to \( P_{\text{nd,\text{max}}} \). The local maximum is chosen so as to allow margin against typical degradation in the link. The global maximum is set such that a reverse link PER better than 1% can be achieved regardless of channel conditions for packets transmitted at 9.6kbps.

If a “GOOD” packet is received in NO DATA mode, the algorithm transitions to DATA-START mode and \( T \) is adjusted as \( T_{\text{new}} = \max(T_{\text{old}} - \Delta_{\text{good,ds}} \cdot P_{\text{min}}) \). If a “BAD” packet is received in NO DATA mode the algorithm transitions to NORMAL mode and \( T \) is adjusted as \( T_{\text{new}} = \min(T_{\text{old}} + \Delta_{\text{bad,ns}} \cdot P_{\text{max}}) \) where \( \Delta_{\text{good,ds}} \) is the adjustment in \( T \) due to receipt of a “GOOD” packet in the NO-DATA mode.

If \( \Delta_{\text{nd}} \) is too large it would result in wasted reverse link capacity, while too small would not ensure that the first transmission after a short silent period has a high probability of being decoded successfully. A nominal setting of \( \Delta_{\text{nd}}\approx0.5\text{dB} \) is used.

Data Start: The algorithm enters this state, when the BSC starts receiving data while in the NO-DATA state. In this state, PCT is reduced at a rate faster than normal for every good frame received in order to compensate for any increase of the PCT in the NO-DATA. The algorithm returns to the NORMAL mode once a “BAD” packet is received.

If a “GOOD” packet is received in DATA-START mode, \( T \) is adjusted as \( T_{\text{new}} = \max(T_{\text{old}} - \Delta_{\text{good,ds}} \cdot P_{\text{min}}) \). If a “BAD” packet is received in NO-DATA mode the algorithm transitions to NORMAL mode. \( T_{\text{new}} = \min(T_{\text{old}} + \Delta_{\text{bad,ns}} \cdot P_{\text{max}}) \) is chosen such that it reduces PCT to maximize reverse link capacity but less than the expected required Pilot Ec/Nt from one packet to the next. Too large a value would result in an adjustment that eventually causes errors that take multiple frames to recover. Therefore \( \Delta_{\text{good,ds}} \leq \Delta_{\text{bad,ns}} \).

Ratchet Mode: ROLPC algorithms adjust the PCT in order to maintain the target PER. However, if the AT is unable to close the reverse link due to temporary shadowing an increase in PCT for bad packets will not reduce the PER as the AT is power limited. The Ratchet mode prevents the PCT

\(^2\) Refer [6] for details
from being set at an incorrect high value and possibly railing at $P_{\text{max}}$. If the PCT is set at an incorrect high value, following improved channel conditions the AT’s would continue to transmit a large excess power until sufficient good packets were received to adjust PCT down.

Under normal operating conditions the average Pilot Ec/Nt is greater than PCT as RCLPC controls the median AT transmit power. The difference between PCT and average Pilot Ec/Nt is a function of vehicle speed. Therefore, if the average Pilot Ec/Nt is less than PCT the AT is transmitting at maximum power and yet unable to reach the level desired at the AN. On detecting this condition the algorithm transitions to the Ratchet mode and the PCT is adjusted only in response to “GOOD” packets and not “BAD” packets, as all received packets will likely result in CRC failures. If the AT is in soft-handoff the algorithm transitions to this mode only if all links satisfy the above mentioned condition.

IV. ROLPC PERFORMANCE

We evaluate settings for $\Delta_{\text{bad},n}$ and show the performance of the ROLPC algorithm in conjunction with higher layer protocols, packet sizes and interarrival times.

A. TEST SETUP

The nominal ROLPC parameter settings used are shown in Table III. The test setup included a single AN and AT with balanced paths in a diversity setup at the AN receiver.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{min}}$ - $P_{\text{max}}$</td>
<td>(-23.5 dB, -20 dB)</td>
</tr>
<tr>
<td>$\Delta_{\text{bad},n}$</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>$\Delta_{\text{good},n}$</td>
<td>0.005 dB</td>
</tr>
<tr>
<td>$\Delta_{\text{good},ds}$</td>
<td>0.015 dB</td>
</tr>
<tr>
<td>$P_{\text{nd},\text{max}}$</td>
<td>-21 dB</td>
</tr>
<tr>
<td>$\Delta_{\text{nd}}$</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>$\Delta_{\text{nd},\text{step}}$</td>
<td>0.010 dB</td>
</tr>
<tr>
<td>$T_{d}$</td>
<td>10 sec</td>
</tr>
<tr>
<td>$N_{\text{nd}}$</td>
<td>0.5 sec</td>
</tr>
</tbody>
</table>

B. STEP SIZE SELECTION $\Delta_{\text{bad},n}$

Since the required PCT is a function of vehicle speed as shown in Figure 4, the speed was varied gradually over the typical range of operation (0-120 km/h) as shown in Figure 6 with constant reverse link transmission at 38.4kbps. Figure 7 shows the complementary CDF of Pilot Ec/Nt as a function of step size for different values of $\Delta_{\text{bad},n}$. A high concentration of errors on the reverse link would have an adverse impact on both the reverse link throughput and possibly on the forward link throughput. A 2-second duration is therefore used to show the concentration of errors. Smaller values of $\Delta_{\text{bad},n}$ result in a long run of burst errors, a longer time to reach the desired PCT setting and longer time to recover from improved channel conditions and therefore in a loss in capacity. Larger values result in a lower concentration of burst errors at the expense of additional interference to other users. $\Delta_{\text{bad},n} = 0.5$ dB is seen to be a reasonable optimization. Figure 7 shows that with $\Delta_{\text{bad},n} = 0.5$ dB the mean Pilot Ec/Nt is lower than that with $\Delta_{\text{bad},n} = 0.25$ for reasons explained above. The variance however increases a function of increasing $\Delta_{\text{bad},n}$.

C. PERFORMANCE OF HIGHER LAYER PROTOCOLS

Figure 8 shows the performance of the ROLPC algorithm for a given vehicle speed (3 km/h) for different packet sizes and inter-arrival times using the settings shown in Table III. The CCDF of the AT transmit power for different types of data transfers: FTP, a 5000-byte packet and a 32-byte packet is shown along with the frequency of errors.
over a 2-second interval for those applications is shown in Figure 8. Figure 9 shows the reverse link physical layer data rates used and the fraction of time spent in each of the ROLPC states.

The 5000-byte packet includes physical layer packets transmitted at the higher data rates. The highest data rate (153.6kbps) requires a large adjustment in PCT resulting in the burst errors. On the other hand the 32-byte packet is transmitted at 9.6kbps. For this case the algorithm transitions between the DATA-START and NO-DATA modes and occasional packet errors result in a transition to the NORMAL mode. The ROLPC algorithm spends most of its time in the NO-DATA mode. The high RL power in case of NORMAL mode. The ROLPC algorithm spends most of its time in the NO-DATA mode. The high RL power in case of NORMAL mode. The ROLPC algorithm spends most of its time in the NO-DATA mode. The high RL power in case of NORMAL mode.

Figure 8 shows the reverse link physical layer data rates used and the fraction of time spent in each of the ROLPC states.

D. ROLPC V/S GENIE-AIDED PCT SETTING

The authors would like to thank the 1xEV team and in particular Fatih Ulupinar for his help with this work.

REFERENCES