Reverse link Rate Control in 1xEV-DO with Adaptive Antenna Arrays

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Abstract—Rate control and distributed reverse link scheduling in CDMA systems are considered. Probabilistic rate allocation with and without token bucket constraints gives mobiles more autonomy in making transmission decisions. A system with adaptive antenna arrays deployed at the base stations is proposed as a generalization to the model with omnidirectional antennas. Uniform linear antenna arrays with a microstrip patch as their constituent element are presented. Their number of elements is varied and their performance is compared to the omnidirectional case, showing substantial throughput gains.

Index Terms—Antenna arrays, distributed reverse link scheduling, rate control, 1xEV-DO, CDMA

I. INTRODUCTION

In recent years, distributed scheduling of mobile users has gained more importance. Probabilistic transmission by mobile devices in the EV-DO system is described in [1], whereas the incorporation of token buckets in the EV-DO Rev A system is discussed in [2]. Consequently, mobile devices are given more autonomy in making transmission decisions, and thus more freedom of action ([3], [4], and [5]). This differs from the traditional aspects of wireless networks, where the base stations maintain full and centralized control in the allocation of the system resources.

In centralized schemes (e.g. maximum C/I [6] and proportional fair [7]), user scheduling is the responsibility of the base station, which normally allocates resources to a single user at a given time instant. Distributed schemes are allowed by several standards for modern 3G/4G cellular networks, e.g., 1xEV-DO Rev A [8]. These standards have introduced mechanisms that give devices greater independence in making transmission decisions best matched to their applications, e.g. deciding when to transmit and at what rate. The price for this flexibility is potentially higher interference, and a corresponding degradation in performance [3], [4]. Consequently, base stations should maintain some control over the interference. They exercise this control by setting a Reverse-link Activity Bit (RAB) on when the load increases, and clearing it otherwise. The RAB is used in conjunction with a token bucket, where tokens are a function of transmission power, and the base station controls the token generation rate and the token bucket depth [3]. The reverse traffic channel rate control algorithm for cdma2000 is presented in [1], where transition from one rate to another is performed by mobile devices in a probabilistic manner based on the value of the RAB. The reverse traffic channel MAC design of cdma2000 1xEV-DO Rev A system is discussed in [2], where an algorithm is presented to update the token generation rate and the token bucket depth based on the computation of the RAB. In this work, we generalize the scenario studied in [1] to the case where adaptive antenna arrays are deployed, then we incorporate token bucket constraints in the system using the approach described in [2].

The motivation behind using adaptive antennas with the reverse link rate control and scheduling algorithm of [1] is due to the high gains and interference mitigation properties of these antennas that can lead to higher SINRs and hence higher network throughput.

In the literature, there are many contributions to investigate the performance gains by using adaptive antenna arrays at CDMA base stations (e.g. see [9], [10], [11], and [12]). For beamforming, two methods are normally considered: fixed beam and steered beam (beam pointing). Fixed beam makes use of a specified number of fixed beams to cover a cell sector whereas beam steering allows directing the beam towards a specific user.

In this work, we investigate the gains achieved by user-specific beamforming when combined with the distributed reverse link rate control scheme of [1]. A beam is formed in the direction of every user in the cell. By direction of a user we mean the direction of arrival of the strongest multipath component of the signal transmitted by that user. Furthermore, a comparison between the results obtained by using antenna arrays with different number of elements is presented.

In Section II, we describe the system model, where we generalize the approach of [1] to the case where adaptive antennas are deployed at the base stations. The reverse link rate control algorithm is described in Section III. In Section IV, we introduce the various antenna arrays used in the simulations and discuss their radiation characteristics. Monte Carlo simulation results of the scenarios with and without adaptive antennas are compared in Section V and the improvements obtained in the former case are discussed. Finally, conclusions are drawn in Section VI.

II. SYSTEM MODEL

In this section, we generalize the approach used in [1] to the case of base stations equipped with adaptive antenna arrays.

The reverse link of the EV-DO system is interference limited since the achievable data rate is strongly influenced by the transmission power used by all the mobile devices. Hence, a device’s transmission decisions are governed by the trade-off between increasing one’s own signal strength and causing interference among other users. Consequently, a user needs to decide what transmission power to utilize and when and how often to transmit.

The EV-DO reverse link incorporates several advanced physical and MAC layer design principles to improve the flexi-

978-1-4244-2202-9/08/$25.00 © 2008 IEEE
ibility of transmission decisions on the reverse link, and more importantly facilitate distributed operation and give devices greater independence [4]. In the Rev A specifications, the pilot assisted transmission guides the choice of the transmission power, and token bucket control influences the frequency (and scheduling) of packet transmissions.

During reverse link transmission in the EV-DO system, each device transmits a pilot signal whose power is controlled by the base station using a fast closed power control loop, such that the pilot power received at the base station from each device is approximately the same, even in case of channel fluctuations. The power transmitted by a user \( i \) in a given time slot \( t \) in order to achieve a data rate \( R_i(t) \) is then related to the pilot power through a proportionality factor that is a function of the desired rate:

\[
P_D^i[R_i(t)] = \text{TTP}^i[R_i(t)] \cdot P_S^i(t)
\]

(1)

Where:
- \( P_D^i \) is the transmission power of user \( i \) at a time slot \( t \) when the transmission rate is \( R_i(t) \),
- \( P_S^i \) is the transmitted pilot power of user \( i \), varied according to the fast inner-loop power control,
- \( \text{TTP}^i[R_i(t)] \) is a proportionality factor function of the rate \( R_i(t) \). It represents the rate to token mapping and scales the transmission power in units of the transmitted pilot power.

It should be noted that, in the above mechanism, the choice of transmission power for the data is de-coupled from the problem of coping with fading and attenuation on the wireless channel, through the fast inner-loop power control of the pilot signal. The fast inner-loop power control keeps the received pilot signal approximately constant, by allowing it to track variations of the wireless channel, so that the data transmission power can be set relative to the pilot power [4]. Although mobile devices are allowed distributed usage of resources at short time scales, control is still exercised by the base stations on the allocation of long-term resources per device. In this way, the access network prevents users from becoming persistently greedy and thus generating too much interference, which in the long-run can degrade system throughput.

The EV-DO Rev A system achieves this long term control through a token bucket. Each device has a bucket of maximum depth \( D \) in which it stores its current credit of power tokens and that is filled at a rate of \( G \) tokens per transmission slot. The number of tokens present in the bucket determines the set of rates at which the device is entitled to transmit [2]. Naturally, a rate-to-token mapping should entail larger amounts of tokens when the rate increases, since this is translated into an increase of transmission power.

The system is assumed to consist of a single cell with \( n+1 \) homogeneous and continuously backlogged users sharing a time-slotted reverse link. The SINR of user \( i \) in slot \( t \) is then given by:

\[
S_i[R_i(t)] = \frac{G[R_i(t)] \cdot G_{loss}(t) \cdot A_i[\phi_i(t)] \cdot P_D^i[R_i(t)]}{\sigma^2 + \sum_{j \neq i} G_{loss}(t) \cdot A_i[\phi_j(t)] \cdot P_D^i[R_j(t)]}
\]

(2)

Where:
- \( G_{loss}(t) \) represents the channel variation experienced by user \( i \) in time slot \( t \). It is a time varying function of the user distance as well as log-normal varying function and fast-fading,
- \( \sigma^2 \) is the thermal noise,
- \( R_i(t) \) is the transmission rate of user \( i \) at time slot \( t \),
- \( G[R_i(t)] = W/R_i(t) \) is the processing gain associated with rate \( R_i \) where \( W \) is the spread-spectrum bandwidth.

For EV-DO systems, \( W = 1.25 \text{ MHz} \),
- \( A_i[\phi_i(t)] \) is the antenna gain due to the beam pointed in the direction of user \( i \), and \( \phi_i(t) \) is the direction of user \( i \) at time slot \( t \). With the assumption of negligible steering errors, \( A_i \) is maximum in the direction of \( \phi_i(t) \) and decreases in the other directions,
- \( A_i[\phi_j(t)] \) is the antenna gain due to the beam pointed in the direction of user \( i \), measured in the direction of \( \phi_j(t) \) of user \( j \) at time slot \( t \). Hence, \( A_i[\phi_j(t)] \) corresponds to the direction of the main lobe, whereas \( A_i[\phi_j(t)] \) corresponds to the direction of side lobes and nulls (unless users \( i \) and \( j \) are in the same direction).

Thus, adaptive antennas will increase the SINR since the desired signal is multiplied by \( A_i[\phi_i(t)] \) (gain in the direction of the main beam) and the interfering signals are reduced due to their multiplication by \( A_i[\phi_j(t)] \), contrarily to the omnidirectional antenna case where both the signal and interference are weighted equally by the receive antenna \( A_i(\phi) \) is the same for all \( i \) and \( \phi \). Since perfect power control is assumed, the received pilot power at the base station is considered to be constant for all users:

\[
G_{loss}(t) \cdot A_i[\phi_i(t)] \cdot P_D^i(t) = \Delta = \frac{\sigma^2}{\varphi - n}
\]

(3)

Where \( 1/\varphi \) is a common target SINR that each pilot signal is trying to achieve [4].

Instead of considering transitions between all available rates as in [1], a simple on-off scheduler is considered in [3]. A user either transmits at a rate \( R \) with a probability \( p \), or does not transmit with a probability \( 1 - p \). However, the average throughput is computed in [4] by assuming it varies linearly with the SINR. In this work, we resort to a more accurate system model by generalizing the system of [1] with multiple rates to the case where adaptive antenna arrays are deployed. Then we consider the algorithm described in [2] to incorporate token bucket constraints into the system.

### III. RATE CONTROL ALGORITHM

The reverse link channel MAC protocol is described in [1]. It defines the rules used by the mobile device to determine its transmission data rate on the reverse link channel. Two mechanisms allow the base station to control the transmission data rate of a given device. First, the mobile device may periodically receive a message from the base station indicating the maximum data rate it may transmit on the reverse link. In this work, the rate limit is assumed to be the maximum allowed rate. Secondly, the mobile device receives a Reverse
Activity Bit (RAB) from each base station in its active set, indicating whether the total reverse traffic channel interference received at the base station is above a certain value. This information determines whether the mobile device may increase or decrease its data rate. The device increases or decreases its data rate in a probabilistic manner. The probabilities governing these transitions are specified by the base station for each mobile device, allowing the network to differentiate the behavior of the reverse traffic channel rate control algorithm among different devices. The following is a summary of the procedure used by a mobile device to determine its reverse link data rate [1]:

1. If \( \text{CombinedRAB} = 1 \), then set \( \text{MaxRate} = \max(\text{LowestAllowedRate}, \text{NearestLowerRate}) \) with probability \( p \) or \( \text{MaxRate} = \text{CurrentRate} \) with probability \( (1 - p) \). The transition probability \( p \) is a function of the current rate. The transition probabilities are specified in Table I.

2. If \( \text{CombinedRAB} = 0 \), then set \( \text{MaxRate} = \min(\text{HighestAllowedRate}, \text{NearestUpperRate}) \) with probability \( q \) or \( \text{MaxRate} = \text{CurrentRate} \) with probability \( (1 - q) \). The probability \( q \) is a function of \( \text{CurrentRate} \). The transition probabilities are specified in Table I.

3. The new transmission data rate may not exceed the limit given by the network, thus, set \( \text{NewRate} = \min(\text{MaxRate}, \text{RateLimit}) \).

4. If the transmit power available at the mobile device is not sufficient to support transmission at \( \text{NewRate} \), then the mobile device decreases \( \text{NewRate} \) to the highest data rate that can be accommodated by the available transmit power.

5. The mobile device transmits at \( \text{NewRate} \).

CombinedRAB is equivalent to the RAB set by the base station of the cell. To determine the value of the RAB, the Rise of interference over the Thermal noise (RoT) is computed. If it is above a certain threshold, the RAB is set to 1; otherwise, it is set to 0. We consider the average interference obtained by averaging the second term in the denominator of (2) over all users. Denoting the result by \( I_0 \), the value of the ratio \( I_0/N_0 \) is computed in order to set (or unset) the RAB.

\[
\frac{I_0}{N_0} = \frac{1}{n+1} \sum_{t=1}^{n+1} G_i^j(t) \cdot A_i[\phi_j(t)] \cdot P_i^j[R_j(t)]
\]

The above discussion does not take into account the incorporation of token bucket constraints. Token buckets allow base stations to prevent users from becoming persistently greedy and thus generating too much interference. The procedure used to add and/or remove tokens from the bucket of each user is described as follows:

1. At each time slot, \( \rho \) tokens are added to the bucket of each user, in condition that the total number of tokens in the bucket does not exceed the depth \( L \).

2. If the user transmits at a rate \( R_i(t) \) at a certain time slot \( t \), then \( \text{TTP}[R_i(t)] \) tokens are removed from the bucket. This way, users requesting high transmission rates are penalized by losing more tokens [4].

### IV. Antenna Arrays

The performance of single antenna elements is poor compared to that of antenna arrays. In an antenna array, the number of elements, the spacing between them, their excitation coefficients, and their relative phases are parameters that can be adjusted not only to increase the antenna gain but also to narrow the beam (i.e., decrease the beamwidth), steer the beam in a given direction, and/or control the side lobes level (by adjusting the excitation coefficients of the antenna array, e.g., using the Dolph-Chebyshev method [13]). These factors determine the array factor which is used in the calculation of the array directivity and consequently the array gain. The total field of an array can be calculated by multiplying the field of a single element at a selected reference point (usually the origin) and the array factor. The array gain is equal to the directivity multiplied by the loss coefficient which in turn depends on the antenna type. When the losses are negligible, the gain is approximately equal to the directivity [13]. Widely used antenna arrays are the uniform linear arrays where the radiating elements are placed on a line with equal spacing and excitation in addition to uniform circular arrays where the radiating elements are uniformly distributed on a circle with equal excitations.

The normalized array factor of an \( N \) element uniform linear array (ULA) with equal amplitude excitation and inter element spacing \( d \) is given by [13]:

\[
\text{AF}_{\text{ULA}}(\theta) = \frac{\sin\left(\frac{N}{2} \psi\right)}{\sin\left(\frac{\psi}{2}\right)},
\]
Fig. 1. Linear Antenna Array Placed Vertically on the z-axis.

where
\[
\psi = kd \cos(\theta) - kd \cos(\theta_0),
\]
(6)

\( \theta_0 \) is the direction of maximum radiation, and \( k \) is the wave number. To steer the beam in the direction \( \theta_0 \), the progressive phase between the elements should be \( -kd \cos(\theta_0) \). Eq. (5) is independent of \( \phi \) since it expresses the array factor of a linear array in the vertical direction, as shown in Fig. 1. Hence, the pattern will be omnidirectional in the azimuth plane. To use the array in adaptive antenna techniques, it should be placed in the azimuth plane instead. Its pattern will still exhibit the same form but its mathematical expression will become more complex. We are interested in this paper by uniform linear antenna arrays.

Fig. 2 shows the normalized array factors of 2-element and 4-element uniform linear arrays. We varied the inter-element spacing in order to obtain narrower main beams with higher directivities while keeping the same maximal side lobe level, and we used the spacing that yielded the best results. An example is shown in Fig. 2 for the 2-element array, whereas for the 4-element array, only the best result is plotted. In the simulations, we used the 2-element array with a spacing of 0.532\( \lambda \), and the 4-element array with a spacing of 0.8\( \lambda \).

As stated previously, the pattern of an antenna array is the product of the element pattern and the array factor. As a constituent element for the array factors shown in Fig. 2, we select a microstrip patch designed in [14] where linear arrays were constructed successfully with the patch as their constituent element. The pattern of the microstrip patch is shown in Fig. 3.

The array patterns obtained by the multiplication of the element pattern of Fig. 3 by the array factors of Fig. 2 are shown in Fig. 4.

The characteristics of the linear arrays obtained by using the patch of [14] are shown in Table II. In Table II, the directivities, half-power beamwidths (HPBW), and the inter-element spacings \( d \) are shown.

<table>
<thead>
<tr>
<th>Array</th>
<th>Directivity (dB)</th>
<th>HPBW (degrees)</th>
<th>( d ) (in ( \lambda ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-element ULA</td>
<td>21.99</td>
<td>44.75</td>
<td>0.5</td>
</tr>
<tr>
<td>2-element ULA</td>
<td>22.33</td>
<td>43.35</td>
<td>0.532</td>
</tr>
<tr>
<td>4-element ULA</td>
<td>29.21</td>
<td>16.31</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**TABLE II**

PROPERTIES OF THE DIFFERENT ANTENNA ARRAYS.

It should be noted that the array factors of Fig. 2 correspond to arrays placed on the vertical direction (z-axis). This position was only used to simplify the forms of the equations since when these arrays are placed along other axes their properties will naturally still be the same but their mathematical expressions will be more complex. However,
in this position, these arrays are broadside arrays having omnidirectional properties in the azimuth (x-y plane). In order to use them as adaptive antennas, we must place them in the azimuth plane, perpendicularly to the vertical direction (z-axis). Still, even in this position, the array factors of linear arrays have major lobes in two opposite directions (e.g. $\phi = 0$ and $\phi = 180$ degrees when placed on the x-axis). But Fig. 3 shows that the element used has very low back lobes. Hence, when the patch is used to form the arrays, its main lobe will enhance the main beam of the array factor ($\phi = 0$) whereas its back lobe will reduce significantly the undesired lobe at $\phi = 180$ degrees. In addition, the multiplication property of the array pattern will lead to side lobes of lower level than those in the array factor. These results can be verified by inspecting Fig. 4.

V. SIMULATION RESULTS

This section presents the simulation results obtained by applying the distributed rate control concept presented in Sections II and III to a cell with a base station equipped with adaptive antennas, and compares the results to the case of omnidirectional antennas. The results are derived using a detailed simulation of the reverse link of the EV-DO Rev A system. The simulation attempts to accurately emulate the impact of the channel on the transmissions from different users, and compares the performance of omnidirectional and adaptive antennas within a single cell. The carrier frequency of the CDMA system was set to 1900 MHz, its bandwidth to $W = 1.25$ MHz, and the target pilot SINR $1/\phi$ to $-17$ dB. The duration of transmission slots was taken to be $16.667$ ms, the frame length on the reverse link of EV-DO. Hence, each device is making scheduling decisions at this time granularity. Users were generated randomly within a cell of 1 km radius. Initial rates for each user were also selected arbitrarily. Each experiment was repeated 100 times, and during each time it was run for 11000 slots. The results of the first 1000 slots were not considered in the averaging in order to allow the system to stabilize. This step is necessary to overcome the effects of the random selection of the initial user rates.

The path loss of user $i$ is of the form:

$$G_i(t) = \frac{\beta}{d_i^\alpha} F(t)$$

In (7), the first factor captures propagation loss, with $\beta$ a constant chosen to be 100, $d_i$ the distance from mobile $i$ to the base station, and $\alpha$ the path loss exponent, which was set to a value of 4 [15]. The second factor, $F(t)$, captures log-normal shadowing (with an 8 dB standard deviation) in addition to flat fading (assumed to be Rayleigh distributed with a Rayleigh parameter $\sigma$ such that $E[\sigma^2] = 1$). An RoT threshold of 5 dB was used to set the RAB to 1 (In Fig. 5, results for an RoT threshold of 3 dB are also shown). The maximum transmit power for each mobile was set to 23 dBm. When the power required by a mobile to transmit at a given rate exceeds the maximum power, the mobile attempts transmission at the nearest lower rate, until it finds a suitable rate. Otherwise, it refrains from transmission.

Fig. 5 shows the average throughput results, obtained by using the different antenna arrays, vs. the number of users. Transition probabilities between the rates are the ones shown in Table I. No token bucket constraints are incorporated. Clearly, adaptive antenna arrays outperform omnidirectional antennas, and the 4-element array is superior to the 2-element array. It can be seen that for a fixed number of users, the average throughput is considerably higher with adaptive antennas. In addition, for a fixed desired average throughput, a system with adaptive antennas can accommodate much more users. For example, fixing the desired throughput at 153.6 kbps (the maximum available rate) and considering a 5 dB RoT threshold, the proposed 4-element linear array can accommodate 18 users (all achieving approximately the desired rate), whereas the 2-element array allows 8 users to achieve the desired rate, compared to only 2 users when omnidirectional antennas are used. When the number of users increases, the rate decreases due to the increase in interference. After a certain limit, users are only able to achieve the lowest allowed rate. Considering the 5 dB threshold on Fig. 5, this limit is reached with 48 users when using the 4-element array, 42 users when using the 2-element array, and 20 users when omnidirectional antennas are used. Fig. 5 also shows that the throughput increases when the system is able to handle a larger interference margin (throughput in the case of a 5 dB threshold is higher than in the case of a 3 dB threshold, especially when adaptive antenna arrays are deployed).

Taking token bucket constraints into account, the results of Fig. 6 are obtained with $p = 50$ and $L = 1500$ tokens. The results of Fig. 5 for the RoT threshold of 5 dB are also shown to facilitate the comparison. Interestingly, the plots representing the token constrained case coincide with those representing the absence of token constraints, except for the maximum value. The effect of adding token bucket constraints is in the reduction of the maximum achievable average throughput. This result is not surprising, since high transmission rates require high transmission power (relative to the pilot power), and hence are penalized by a greater amount of tokens, thus draining the token bucket of the greedy users, and consequently reducing the throughput. Besides this rate limitation effect, the same conclusions as in the absence of
token constraints can be drawn, regarding the superiority of adaptive antenna arrays, namely the 4-element array.

VI. CONCLUSIONS

Distributed rate control in a probabilistic manner was studied in the presence of adaptive antennas at the base station. Results were compared between different linear antenna arrays, and the omnidirectional case. Scenarios studied included the presence and absence of token constraints, and different QoS requirements. The directivity, narrow beams, and low side lobe levels of adaptive antenna arrays lead to a major decrease in interference and hence an increase in SINR, and consequently in the average achieved throughput. It was shown that with adaptive antennas, the system can tolerate more users achieving high throughput simultaneously. The effect of adding token constraints was a reduction of the maximum achieved throughput, due to the limitation of the average transmitted power.

REFERENCES