ITERATIVE POWER CONTROL FOR MULTIMEDIA WIRELESS COMMUNICATIONS

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ABSTRACT

This paper addresses uplink power control for terminals that transmit multimedia signals in a CDMA cell. The aim of the power control is to minimize total power consumed by the terminals due to signal compression and transmission while the end-to-end distortion for each terminal is kept at a predetermined value. We propose a distributed iterative power control algorithm and prove convergence. The simulations for Gauss-Markov source with transform coder and H.263 encoded video signal show that the proposed algorithm achieves the jointly optimal power values for most of the channel conditions. It is also observed that the algorithm outperforms non-adaptive multimedia transmission in terms of power consumption.

1. INTRODUCTION

Power control for uplink cellular systems allocates power to terminals to satisfy quality of service (QoS) constraints. Most research on power control focuses on voice and data transmission. In these cases, the required QoS objective is to have predetermined signal-to-interference-noise ratio (SINR) for the terminals at the base station while minimizing the transmission power [1], [2]. Multimedia signals on the other hand have characteristics that necessitate a different type of power control. First of all, one of the main concerns in multimedia is to keep the end-to-end distortion (D) of the signal at a constant value. The distortion occurs because of the lossy source compression and channel errors, and it depends on both the channel signal-to-interference-noise-ratio (SINR) and the video encoder parameters such as complexity and rate. Also multimedia signal compression consumes power comparable to transmission power, which necessities joint optimization of source encoder and transmitter to minimize total power consumption. This was investigated for a single-user system in [3]-[5]. In a multiuser system, each user causes interference to others and the power allocation becomes a multivariate problem depending on the source encoder and transmission parameters of all users. In centralized power control schemes, a central controller collects the operating parameters of all users in the network, such as channel conditions, required end-to-end distortion, etc. and finds the optimal operating powers of all users by jointly optimizing the system [6]. However, centralized schemes have exponentially increasing complexity with the number of users in the network and large delay since the optimization has to be redone each time users enter or leave the network.

Our goal in this paper is to find an iterative power control algorithm for the uplink of K users that transmit multimedia signals in a CDMA cell such that the total power consumed, including compression and transmission power, is minimized subject to a predetermined end-to-end distortion at each terminal. Our algorithm updates the compression parameters (complexity, rate) and transmission power of each user only based on the total interference plus noise level of that user, and iterates among the users. Hence at each step of the algorithm, we carry out a single user optimization, thus lowering the complexity. We show that the algorithm converges and most of the time it is able to find optimal power values computed jointly. Even when it reaches a suboptimal power level, it still significantly outperforms non-adaptive power allocations. One of the advantages of an iterative scheme is that it easily adapts to changing conditions, such as link SINR's and number of users. We show both analytical and simulation results for Gauss-Markov and H.263 compressed video sources.

In Section 2, the system model used in the paper is introduced. In Section 3, we describe our iterative power control algorithm. In Section 4, parameters of the power control algorithm are analytically derived for Gauss-Markov Sources and H.263 encoded video signals. The performance evaluation and simulation results are shown in Section 5. We conclude the paper in Section 6.

2. SYSTEM MODEL

We assume there are K users communicating with a base station in a CDMA cell with chip rate of R_c chips/s. We consider a packet length of M bits and constant channel gains for each packet so that the received power at the base station is $P_{rec,i} = h_i P_{t,i}$ Watts where h_i is the channel gain of user i and $P_{t,i}$ is the transmission power. The channel gains, h_i, $i = 1, \dots, K$, are known at the base station. We do not consider channel coding in the system. Compressed bits are packetized and transmitted over the channel. It is assumed that the overheard control bits are small compared to the packet length, so in the analysis they are not incorporated. We will study two types of sources: An abstract Gauss-Markov Source and H.263 compressed video source.

The transmitted multimedia signal suffers from the distortion caused by lossy source compression and transmission errors. The distortion caused by the source compression, D_s depends on the complexity of the encoder, β, and the compression rate R_s, used by the encoder. For fixed distortion D_s, a more complex encoder results in higher β and lower compression rate R_s (bits/sample). Examples of β include, transform dimension for a transform coder, or the INTER rate for H.263 video coder. The distortion introduced by the channel, D_t, depends on the SINR γ at the base station, bit rate R_s and complexity β. Note that high β produces a more compressed stream which will be more susceptible to channel errors. As a result, the total end-to-end distortion of the multimedia signal for user i can be written as $D_{tot,i} = D_{s,i}(\beta_i, R_{s,i}) + D_{t,i}(\beta_i, R_{s,i}, \gamma_i)$.

The total power consumed by the user to transmit compressed multimedia signal depends on the power consumed by the source encoder and transmission power. As the complexity of the encoder, β,

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increases, the compression power increases. The compression power is expressed in $P_s(\beta)$, which is in general of the form $P_s(\beta) = u_i\beta + v_i$ Watts where u_i and v_i are constants that depend on implementation [5], [6]. On the other hand, the power consumed by transmitting the compressed bits of user i is proportional to the required SINR, γ_i, which can be written as

$$\gamma_i = \frac{R_c}{R_{s,i} f_s} \frac{h_i P_{t,i}}{\sum_{j \neq i} h_j P_{t,j} + \sigma^2} \quad (1)$$

where R_c is the chip-rate (chips/s), $R_{s,i}$ is the compressed bit rate (bit/sample), f_s is the source sampling rate (sample/s) and σ^2 is the noise power at the receiver (Watts).

Since complexity, β, affects the error resilience of the compressed bit stream, the required error rate to guarantee a predetermined end-to-end distortion, and hence required SINR γ_i depends on β_i. Hence, the total power for user i is,

$$P_{tot,i} = P_{s,i}(\beta_i) + P_{t,i}(\beta_i, R_{s,i}, \gamma_i) \quad (2)$$

The total power optimization problem in a K user system subject to QoS constraints becomes

$$\begin{aligned} \text{Minimize} \sum_{i=1}^{K} P_{tot,i} &= \sum_{i=1}^{K} P_{s,i}(\beta_i, R_{s,i}) + P_{t,i}(\beta_i, R_{s,i}, \gamma_i) \\ \text{subject to } D_{tot,i} &= D_{o,i},\ i = 1, \ldots, K \end{aligned} \quad (3)$$

For details of the power and distortion models for Gauss-Markov and video sources used in this paper, see [5]. Note that usually the search space for the complexity β is discrete, which leads to discrete search spaces for R_s and γ as well.

As can be observed from (1), in a multiuser CDMA system, the transmission power of any user i depends on the interference power observed, $P_{int,i} = \sum_{j \neq i} h_j P_{t,j}$. Therefore the transmission power of user i depends not only on its channel condition, h_i and system parameters, β_i and $R_{s,i}$, but also to the interfering users' channels, h_j and transmission powers P_j as well, with $j \neq i$. This suggests that for search spaces of parameters $\beta \in \{\beta^1, \ldots, \beta^{M_\beta}\}$, $R_s \in \{R_s^1, \ldots, R_s^{M_{R_s}}\}$ and $\gamma \in \{\gamma^1, \ldots, \gamma^{M_\gamma}\}$ for all users, the optimization problem in (3) requires a $(M_\beta \times M_{R_s} \times M_\gamma)^K$ dimensional computations. In [6], a novel algorithm to decrease the complexity of joint optimization is proposed. It is shown that in a multiuser system, for each β^k, $k \in \{1, \ldots, M_\beta\}$, of user i, there exists a unique $(R_{s,i}, \gamma_i)$ pair that minimizes the transmission power of that user independent of the interference power. Thus, the joint total power optimization is performed over only the β space of the users in the network, and the algorithm has complexity M_β^K.

However, even though the proposed algorithm in [6] decreases the complexity of the joint optimization significantly, the joint search over the $\beta \in \{\beta^1, \ldots, \beta^{M_\beta}\}$ space of all users and the assignment of transmission powers based on calculated $\gamma_1, \ldots, \gamma_K$ values necessities the centralized power control. Furthermore, the calculations need to be repeated every time the operating environment changes.

In the iterative power control scheme we propose in this paper, the power optimization is based on single user optimizations done iteratively. Optimization for each user is performed with respect to total observed interference power, P_{int} for that user only. Thus, the optimization is carried over a single user's parameter space, without considering the other users' operating parameters. As a result, the iterative algorithm provides the benefits of distributed power control algorithms described in [2].

3. ITERATIVE POWER CONTROL ALGORITHM

In this section we propose an iterative power control algorithm to solve (3). For iterative power control, we use the framework given in [2] and modify the algorithm for multimedia to obtain a converging power control scheme.

In a system with K users, to satisfy SINR requirements of the users, $\gamma_1, \ldots, \gamma_K$, we need $\mathbf{P_t} \geq \mathbf{I}(\mathbf{P_t})$, where $\mathbf{P_t} = (P_{t,1}, \ldots, P_{t,K})$, $P_{t,i}$ denoting the transmission power and $\mathbf{I}(\mathbf{P_t}) = (I_1(\mathbf{P_t}), \ldots, I_K(\mathbf{P_t}))$, $I_i(\mathbf{P_t})$ denoting the iterative function. Accordingly, as given in [2], $\mathbf{I}(\mathbf{P_t}) = (I_1(\mathbf{P_t}), \ldots, I_K(\mathbf{P_t}))$, is called *standard iterative function* and the iterative power control algorithm $\mathbf{P_t}(t+1) = \mathbf{I}(\mathbf{P_t}(t))$ converges to the minimum optimal power values if $\mathbf{I}(\mathbf{P_t})$ satisfies the following three conditions:

$$\mathbf{I}(\mathbf{P_t}) > 0 \quad (4)$$

$$\mathbf{I}(\mathbf{P_t}) \geq \mathbf{I}(\mathbf{P'_t}) \text{ such that } \mathbf{P_t} \geq \mathbf{P'_t} \quad (5)$$

$$\text{For } \alpha > 1,\ \alpha\mathbf{I}(\mathbf{P_t}) > \mathbf{I}(\alpha\mathbf{P_t}) \quad (6)$$

where the vector inequalities $\mathbf{P_t} > \mathbf{P'_t}$, $\alpha\mathbf{I}(\mathbf{P_t}) > \mathbf{I}(\alpha\mathbf{P_t})$ and $\alpha\mathbf{I}(\mathbf{P_t}) > \mathbf{I}(\alpha\mathbf{P_t})$, require strict inequalities componentwise. In data or voice transmission, where each user tries to minimize its transmission power for a predetermined SINR value γ_i without considering joint power optimization of source compression and transmission, the iterative function of user i can be written as ;

$$I_i(\mathbf{P_t}) = \frac{R_{s,i} f_s \gamma_i}{h_i R_c}(P_{int,i} + \sigma^2) \quad (7)$$

In [2] it is shown that the properties in (4)-(6) hold for the iterative function given in (7).

On the other hand, the iterative function of multimedia signals with joint source compression and transmission power optimization has different characteristics. For different interference plus noise power ranges, the total power optimization of the user requires different compression complexities, β. Specifically, when the interference plus noise power observed by the user increases, in order to minimize the total power, the source encoder compresses the signal more to represent it with fewer bits, which increases the compression complexity, β and decreases bit rate R_s. Moreover, as noted before, it is shown in [6] that for each compression complexity β^k, there exists one optimal $(R_{s,i}, \gamma_i)$ pair for any user i. Thus, contrary to the voice and data transmission, where SINR γ_i and bit rates $R_{s,i}$ are constant, in joint power optimized multimedia communication, the γ_i values and $R_{s,i}$ change with compression complexity, thus with interference. As a result the iterative function of each user i, represented in (7), depends on the operating compression complexity, β_i. There exist specific interference power values, $P_{int}^{\beta^k \to \beta^l}$, $\beta^l > \beta^k$, which cause the compression complexity to change from one level say β^k, to another β^l, and temporarily decrease $I_i(\mathbf{P_t})$ and the transmission power, in order to minimize the total power of the user. Note that increasing interference plus noise power forces a user to operate at a higher complexity, ensuring $\beta^l > \beta^k$ [5]. Thus property (5) is violated. We will denote the corresponding optimal transmission power at $P_{int}^{\beta^k \to \beta^l} - \epsilon$, for small ϵ, as $P_t^{\beta^k \to \beta^l}$.

Figure 1 shows the relation of jointly optimized total power, transmission power and optimal compression complexity β with respect to the interference plus noise power for a single user transmitting encoded Gauss-Markov source. The source is compressed with a transform coder and the compressed bits are transmitted over the AWGN channel, using parameters in [5]. As discussed, the optimal transmission power, $P_{t_{optimal}}$, that is the iterative function of user i, $I_i(\mathbf{P_t})$, temporarily decreases around breakpoint interference plus

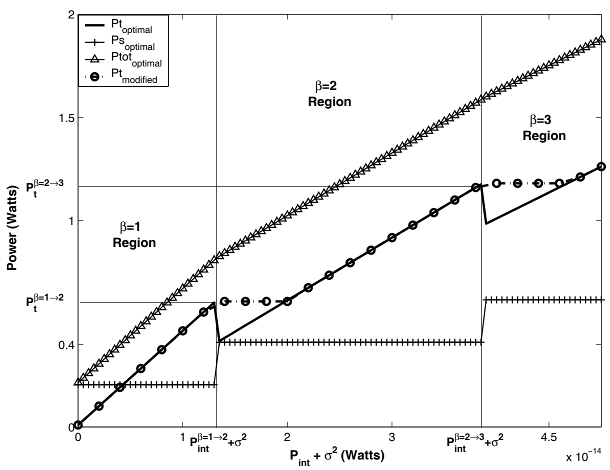

Fig. 1. Optimized transmitter power vs interference plus noise power for Gauss-Markov source

noise powers, and then continues to increase. To have an iterative function that satisfies (4)-(6) we propose a modified power control algorithm next.

3.1. Modified Iterative Algorithm

In order to assure that the iteration $\mathbf{P_t}(t+1) = \mathbf{I}(\mathbf{P_t}(t))$ converges for multimedia applications, we propose the following modifications in the iterative algorithm.

Before starting iteration, each user calculates the breakpoint transmission power set $\{P_t^{\beta^k \to \beta^l}\}$ for each $\beta^l > \beta^k$, such that the optimal β leads from β^k to β^l as interference increases. At each iteration step, the following single user power optimization for user i to keep end-to-end signal distortion $D_{tot,i}$ constant at $D_{o,i}$ is done at the base-station

$$\min_{\beta, R_s} P_{tot,i}(\beta_i, R_{s,i}, \gamma_i) \text{ such that } D_{tot,i} = D_{o,i}$$

The optimization inputs the total interference plus noise power $P_{int,i} + \sigma^2$ and finds the optimal operating parameters β_i^*, $R_{s,i}^*$, γ_i^*. For $\beta_i^* = \beta^l$, the corresponding transmission power $P_{t,i}^*$ can be found as $P_{t,i}^* = \frac{R_{s,i}^* f_s \gamma_i^*}{h_i R_c}(P_{int,i} + \sigma^2)$. Based on this optimization, the modified iterative function for user i is defined as:

$$\tilde{I}_i(\mathbf{P_t}) = \max(P_{t,i}^*, P_{t,i}^{\beta^k \to \beta^l}, \beta^k < \beta^l) \tag{8}$$

where $P_{t,i}^{\beta^k \to \beta^l}$ is the break-point transmission power for the transition from β^k to β^l. Note that this assures that the iterative function to behave as $P_{t_{modified}}$ in Figure 1, thus ensuring monotonicity with respect to $P_{int} + \sigma^2$ as required by (5) and (6).

Based on $\tilde{I}_i(\mathbf{P_t})$, the modified iterative power control algorithm of user i for the power optimized multimedia signals can defined as:

$$P_{t,i}(t+1) = \tilde{I}_i(\mathbf{P_t}(t)) \tag{9}$$

Algorithm:

1. $t = 0$; for all users $i \in \{1, \ldots, K\}$
   $P_{t,i}^{(0)} = 0, P_{s,i}^{(0)} = 0, P_{tot,i}^{(0)} = 0$
2. At iteration step t; for all users $i \in \{1, \ldots, K\}$
   $P_{t,i}(t) = \tilde{I}_i(\mathbf{P_t}(t))$ where $\tilde{I}_i(\mathbf{P_t}(t))$ is defined as in (8)
3. Go back to step (2) until $P_{tot,i}^{(T)} \simeq P_{tot,i}^{(T-1)}$, $P_{t,i}^{(T)} \simeq P_{t,i}^{(T-1)}$ and $P_{s,i}^{(T)} \simeq P_{s,i}^{(T-1)}$ for all users $i \in \{1, \ldots, K\}$.

3.2. Convergence of the Algorithm

Proposition: $\tilde{I}_i(\mathbf{P_t})$ given in (8), is a standard iterative function satisfying the three conditions (4)-(6). Hence the iterative power control, expressed in (9), converges.

Proof: It is easy to see that $\tilde{I}_i(\mathbf{P_t}) > 0$ from (8).

Let $\tilde{I}_i(\mathbf{P_t})|_{\beta^l}$ denote the modified iterative function with optimal compression complexity $\beta_i^* = \beta^l$. Let $\mathbf{P_t} \geq \mathbf{P_t'}$. If optimal complexity of P_t' is again β^l, then $\tilde{I}_i(\mathbf{P_t}) \geq \tilde{I}_i(\mathbf{P_t'})$ and (5) is satisfied. Otherwise P_t' results in some $\beta^k < \beta^l$. From (8), $\tilde{I}_i(\mathbf{P_t})|_{\beta^l} \geq P_{t,i}^{\beta^k \to \beta^l} \geq \tilde{I}_i(\mathbf{P_t'})$ and (5) is satisfied.

Also, let $I_i^{non}(\mathbf{P_t})|_{\beta^k}$ denote the non-adaptive iterative function such that, the user i operates at constant β^k value for any interference. Note that $I_i^{non}(\mathbf{P_t})|_{\beta^k}$ corresponds to the *standard iterative function* given in [2]. Apparently, for $\alpha > 1$, $\alpha\tilde{I}_i(\mathbf{P_t})|_{\beta^k} > I_i^{non}(\alpha\mathbf{P_t})|_{\beta^k}$, Also, $I_i^{non}(\alpha\mathbf{P_t})|_{\beta^k} > \tilde{I}_i(\alpha\mathbf{P_t})|_{\beta^l}$, where $\beta_l > \beta_k$, since the optimization decreases the transmission powers of the users. Thus, $\alpha\tilde{I}_i(\mathbf{P_t}) > \tilde{I}_i(\alpha\mathbf{P_t})|_{\beta^l}$.

4. BREAKPOINT TRANSMISSION POWERS AND COMPLEXITY ANALYSIS

The modified algorithm given in (9), with the iterative function (8) requires the knowledge of break-point transmission powers of each user in the iteration. The break-point transmission power $P_t^{\beta_k \to \beta_l}$ satisfies

$$P_{s,i}(\beta^k) + P_{t,i}(\beta^k, R_s^k, \gamma^k) = P_{s,i}(\beta^l) + P_{t,i}(\beta^l, R_s^l, \gamma^l) \tag{10}$$

where and R_s^k, γ^k and R_s^l, γ^l are the optimal parameters corresponding to β^k and β^l. These optimal parameters, which are independent from the channel condition of the user and the interference power, can be found using [6]. After obtaining the R_s and γ values for the corresponding β, using (1) and (10), the break-point interference power, $P_{int,i}^{\beta^k \to \beta^l}$ and the corresponding break-point transmission power value, $P_{t,i}^{\beta^k \to \beta^l}$ can be found easily.

Using the proposed approach, the break-point transmission powers for the Gauss-Markov Source that is encoded with the transform coder, for $\beta^l > \beta^k$ can be found as

$$P_t^{\beta^k \to \beta^l} = \frac{c_s f_s (\beta^l - \beta^k) R_s^k \gamma^k}{R_s^k \gamma^k - R_s^l \gamma^l} \tag{11}$$

For the H.263 encoded video signals, we have

$$P_t^{\beta^k \to \beta^l} = \frac{c_s b_s R_s^k (\frac{1}{\beta^k} - \frac{1}{\beta^l}) \gamma^k}{R_s^k \gamma^k - R_s^l \gamma^l} \tag{12}$$

where c_s, f_s, b_s are the power consumption parameters given in [5].

Note that for both sources, the break-point transmission powers do not depend on the channel conditions. Hence, the break-point, $P_t^{\beta^k \to \beta^l}$, values for each user can be computed *offline* before starting iteration.

The overall complexity of the algorithm depends on the number of the computations done at each iteration step and the number of iterations for convergence. At each iteration step, each user performs single user optimization which requires M_β computations by applying the algorithm given in [6]. Since the breakpoint transmission power values, $P_t^{\beta^k \to \beta^l}$, are found offline, they are not computed at each iteration step. Hence if the proposed algorithm converges in N_{it} iteration steps, it has the overall complexity related to $K \times N_{it} \times M_\beta$.

5. PERFORMANCE EVALUATION AND SIMULATION RESULTS

In this section, the comparison between our proposed iterative algorithm and joint optimization will be made through simulations. For the power models and compression schemes, the set-up and parameters given in [5] are used.

In Figure 2, the iterative and joint optimization of 4 users each using Gauss-Markov Sources, compressed with transform coder can be seen. Three of the users have fixed channel gains, $h_i = 1.2 \times 10^{-16}$ for $i = 2, 3, 4$. The joint total power of four users as a function of h_1 is shown as $P_{tot,all_{joint}}$ whereas the total power of all users once the modified iterative algorithm converges is labelled as $P_{tot,all_{mod}}$. The figure also shows the comparison of jointly optimized and modified iterative power values of user 1. As can be seen from the figure, the modified iterative algorithm converges to the joint optimal power values for most of the channel conditions and converges to suboptimum values close to optimal for a small range of the channel gain, h_1. The maximum loss in the simulation w.r.t optimal is around 11%.

Figure 3 shows the jointly optimized total power and modified iterative total power of the user 1 in a two-user system, in which both of them transmit video sequence "mother-daughter.qcif" compressed with H.263 encoder. The simulation shows the power values for a channel gain range of user 1, h_1, whereas user 2 has a fixed channel gain, $h_2 = 1.7 \times 10^{-17}$. The plot also shows the non-adaptive total power values of the user for the two constant parameter sets $\{\beta^1, R_s^1\} = \{2, 74.68\}$ and $\{\beta^2, R_s^2\} = \{33, 14.20\}$. Even though the proposed algorithm has deviation from the joint optimization in a small range of h_1, it again converges to the optimal total power in most of the channel conditions. The maximum percentage error is around 12%. Note that the modified algorithm outperforms the non-optimized case, i.e. when the user operates at constant parameters.

In all our simulations, we observed the number of iterations needed for the algorithm to converge, N_{it}, is linear in the number of users. Hence the complexity scales polynomially with the number of users as opposed to exponential [6].

6. CONCLUSION

In this paper, we propose a distributed iterative power control algorithm for terminals transmitting multimedia signals in a CDMA cell. In each iteration step, each terminal jointly optimizes the sum of its own source encoder and transmitter powers subject to predetermined end-to-end distortion at the base station. It is shown that with some simple modifications in the iterations, the proposed algorithm is guaranteed to converge. The simulations show that the algorithm converges to the optimum power values in most cases, or to suboptimal values close to the optimal power. The algorithm also provides flexibility over the existing centralized power control schemes as it can easily adapt to the changing network conditions.

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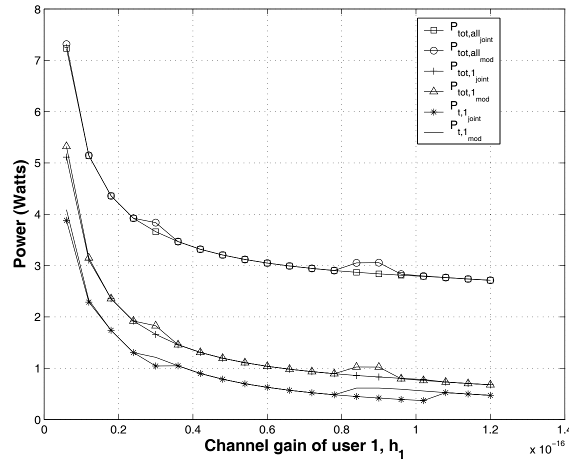

Fig. 2. Comparison between Joint Optimization and Modified Iterative Algorithm: Gauss-Markov Sources

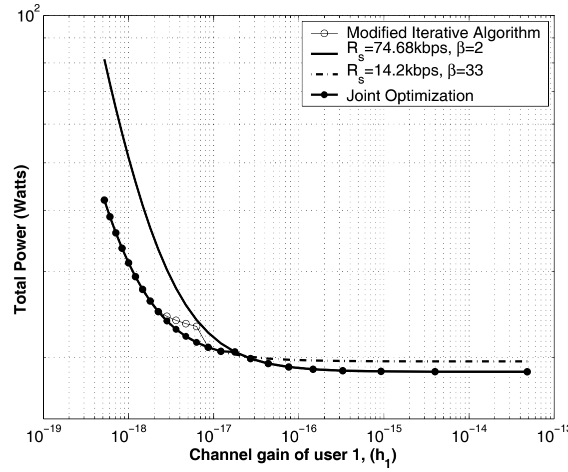

Fig. 3. Comparison between Joint Optimization and Modified Iterative Algorithm: mother-daughter.qcif video sequence compressed with H.263 Video Coder

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