Complexity-bounded Power Control in Video Transmission over a CDMA Wireless Network

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Abstract— **In this work, we consider a CDMA cell with multiple terminals transmitting video signals. The concept of a utility function is used to maximize the number of received picture frames with adequate quality per Joule of energy. For a reconstructed signal at the video decoder, the quality is controlled by the encoded bit rate, compression complexity as well as received signal-to-interference-noise ratio (SINR). In this work video quality is measured in peak signal-to-noise ratio (PSNR) rather than SINR. We find that for a given compression complexity, maximum utility is achieved when the product of bit rate and required SINR is minimized. This maximum usually occurs at maximum video coding complexity. We also investigate the capacity in terms of the number of users that can be supported simultaneously for this system, and how the total utility varies with the number of users in this system. This can be used as admission policy by the central station.**

I. INTRODUCTION

Power control provides each terminal adequate quality of service without causing unnecessary interference to other terminals. In this paper, we focus on power control for video transmission in the uplink of a single CDMA cell. Our goal is to receive video frames at guaranteed quality with the least amount of transmission energy. When a video signal is compressed and transmitted, there is distortion (D) between the original video signal and reconstructed signal due to quantization and channel errors. This distortion is controlled not only by received signal-to-noise-interference ratio (SINR), but also video encoder parameters. In this paper, we parameterize the video coder by the bit rate and a complexity factor. In general, there is more than one set of $\{$bit rate, complexity, SINR$\}$ that can provide adequate quality. Thus it is natural to pose the question as to which one to choose. In this work, we consider how to adjust the source coder parameters (complexity and source rate) and transmission power (which controls SINR) simultaneously to maximize a defined utility, which measures the number of video frames received at guaranteed quality per Joule.

The concept of utility function is borrowed from microeconomics to describe the satisfaction experienced by a person using some service [1]. For data transmission, the utility is interpreted as the number of information bits received per Joule of energy expended [1]. Maximum utility is pursued in both distributed and centralized ways. In [2], [3], the quality per Joule is defined as the utility function for image/video transmission and is maximized for each user. In some applications, the optimal quality achieved by [2], [3] may not be acceptable to the users. (What is more, Nash equilibrium is not necessary the Pareto optimum.) In this work, We use a utility definition that guarantees the desired received video quality.

In Section II, we formally define the utility at each terminal and investigate how to adjust the parameters $\{$bit rate, complexity, SINR$\}$ among all terminals to maximize the utility of each terminal. Our study shows that the optimal (i.e. corresponding to maximum utility) encoded bit rate and corresponding SINR are unique to given compression complexity, provided that the video characteristics, the video codec and the modem are fixed. An important finding from our study is that the utility can be maximized by maximizing a quality factor q that depends on the product of rate and SINR. If the video encoder can change complexity, we find that the maximum quality factor (and consequently utility) occurs at the highest complexity. For this reason, this algorithm is called complexity-bounded resource allocation. The effect of different video scenes is also considered. In Section III, we examine the performance of the system. The capacity in terms of the number of users that can be supported simultaneously and the total utility of all users are evaluated. These parameters can be used for admission policy by the central station. Discussion about this algorithm and work in progress are presented in Section IV.

II. MAXIMIZING UTILITY AT INDIVIDUAL TERMINALS

A. Utility Function and Its Relation with Source Coding and Transmission Parameters

Two important objectives in video transmission over a wireless network are higher quality video pictures at the receiver and longer battery life. In this work, we consider the uplink of a single cell system, and target a constant quality at the video receiver. More specifically, the video encoded at a frame rate f_r satisfies an average target quality. Our goal is to maximize the utility function defined as the number of video frames with certain quality received per Joule. Let N be the number of users in the cell, the problem can be formulated as:

Maximize $U_i = \frac{f_r}{P_i}$, $i = 1, \cdots, N$, *for the* i^{th} *user, where* P_i *is the power consumed by user* i *subject to quality requirement.*

We observe that maximizing utility for the i^{th} user is equivalent to minimizing P_i under a quality constraint and fixed frame rate f_r. Note that by formulating the design objective as to maximizing utility at individual terminals, we are intrinsically assuming that optimizing the utility of

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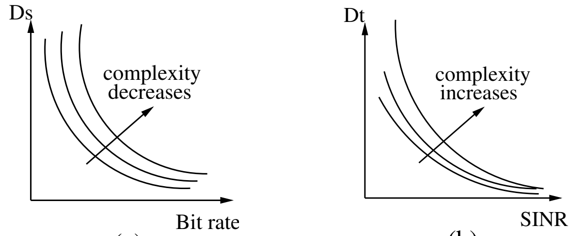

(a) (b)

Fig. 1. Distortion caused by (a) lossy compression and (b) transmission errors.

one terminal does not adversely affect the utility of other terminals. This is true because, for each terminal, the target distortion determines the required SINR and correspondingly transmission power for given rate and complexity. This will be clear from the result given in Sec. B (4). It turnes out that the interference between users only comes into play as a feasibility region for possible operating points. As long as the points are chosen from the feasible region, one can individually maximize the utility at each user. In this work, P_i is considered as transmission power. It can be extended to include source compression power consumption [4].

Peak signal-to-noise ratio (PSNR) is a common measure of video quality, defined as $\mathrm{PSNR} = 10\log_{10}\frac{255^2}{D}$, where D is the distortion measured in Mean-Squared-Error (MSE) between the original signal and reconstructed signal at the receiver. Video quality suffers from both lossy source compression and transmission errors. For the source compressor of the i^{th} user, the operational distortion-rate (DR) function $D_s(R_{s,i}, \beta_i)$ is controlled by the bit rate $R_{s,i}$ (kbps), and encoder complexity, denoted by β_i. Generally, $D_{s,i}$ decreases when bit rate or complexity increases as shown in Fig. 1(a). In this paper, the common DR function is extended by complexity because it controls not only coding efficiency, but also error resilience and compression power consumption. For example, in a H.263 compliant video coder [5] which employs periodic INTRA update scheme, each macroblock is encoded in INTRA-mode at an interval of T frames, other macroblocks are encoded in INTER-mode. The INTER rate defined as $\beta = \frac{T-1}{T}$ denotes the complexity. As β increases, more macroblocks are encoded in INTER-mode and the encoder has a higher coding efficiency. On the other hand, the compressed signal becomes more vulnerable to channel errors.

The use of motion estimation makes a compressed bit stream very sensitive to transmission errors and causes error propagation [6]. The amount of this channel error induced distortion is the difference between the overall distortion D_i and the distortion caused by compression, i.e., $D_{t,i} = D_i - D_{s,i}$. This additional distortion at the decoder $D_{t,i}(\beta_i, \gamma_i)$ can be described as a function of complexity β_i and received SINR γ_i. Since error propagation stops at INTRA macroblocks, $D_{t,i}$ increases as complexity increases (there are less INTRA-mode macroblocks). The error rate seen at the decoder is reduced when SINR increases. Hence $D_{t,i}$ decreases as SINR increases. This is illustrated in Fig. 1(b).

If parameters for both source coding and transmission are configurable, the distortion can be allocated between the source coding and transmission to maximize the utility function. For example, as described in Fig. 2, when complexity β_i is given, to meet total distortion requirement $D_s(R_{s,i}, \beta_i) + D_t(\beta_i, \gamma_i) = D_{i,0}$, the minimum required SINR γ_i and the bit rate $R_{s,i}$ are adjusted jointly. As more bits are used by the source encoder, the distortion caused by lossy compression is lower, hence more distortion caused by transmission errors is tolerable. In other words, a lower SINR is sufficient for the same video quality. On the other hand, when the bit rate is fixed, an increase in complexity reduces $D_{s,i}$. To keep distortion D_0, we allow a larger $D_{t,i} = D_0 - D_{s,i}$ at the decoder. However, since the increase in complexity has made the encoded bit stream more sensitive to channel errors, whether or not SINR decreases depends on the actual amount of decrease/increase in $D_{s,i}$ and $D_{t,i}$ caused by the change of complexity β_i. This is also illustrated in Fig. 2. This tells us that many possible vectors of {bit rate, complexity, SINR} are able to maintain adequate quality.

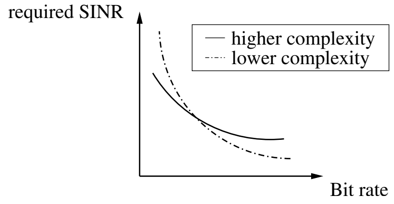

Fig. 2. Minimum required SINR for fixed distortion D_0 at different complexity.

As explained above the bit rate, complexity of the video encoder and received SINR control quality of the received video. They also play an important role in controlling power consumption since the transmission power is proportional to the product of the bit rate and SINR. Given a level of compression complexity, the opposite trend in bit rate and SINR has conflicting effects on power consumption. For instance, a lower bit rate requires less power for a fixed SINR, and a higher SINR requires more power for a fixed bit rate. In the following, we first examine, for a given complexity, how the combination of the bit rate and SINR required to achieve a target quality affects the transmission power (and hence the utility). By evaluating the achievable utility over the feasible range of the complexity, we will determine the optimal complexity, bit rate, and SINR combination that yields the highest utility.

B. System model

We assume all N mobile terminals use the same packet length of M bits. Each packet consists of L information bits, and additional bits for channel coding (generally including both Forward Error Correction (FEC) and Cyclic Redundancy Code (CRC)). When an error is detected based on CRC, error concealment is implemented at the video decoder. In other words, for source bit rate of $\mathbf{R_s} = [R_{s,1}, R_{s,2}, \cdots, R_{s,N}]$, the transmission bit rate is $\mathbf{R} = \frac{M}{L}\mathbf{R_s}$. The path gains are specified by $\mathbf{h} = [h_1, h_2, \cdots, h_N]$. The chip rate R_c is fixed. σ^2 is the noise power in the base station receiver.

C. Maximizing Utility for Given Complexity

1) Maximizing Utility for Given Bit Rate: Given complexity $\boldsymbol{\beta} = [\beta_1, \beta_2, \cdots, \beta_N]$ and rate $\mathbf{R_s} = [R_{s,1}, R_{s,2}, \cdots, R_{s,N}]$, we can determine the corresponding SINR requirement $\Gamma(\mathbf{R_s}) = [\gamma_1(R_1),\ \gamma_2(R_2),\ \cdots,\ \gamma_N(R_N)]$ that satisfies the quality constraint at each terminal. We would like to determine the maximum utility achievable by each user. The problem can be formulated as:

Maximize $U_i = \frac{f_r}{P_i}$ *(Minimize* P_i*),* $i = 1, \cdots, N$*, subject to*

$$\left(\frac{E_b}{N_0}\right)_i = \frac{R_c}{R_i}\frac{h_i P_i}{\sum_{j\neq i} h_j P_j + \sigma^2} \geq \gamma_i(R_i) \tag{1}$$

$$0 < P_i \leq P_{i,max} \tag{2}$$

$$D_i(R_{s,i}, \beta_i, \gamma_i) = D_{i,0} \tag{3}$$

where $D_{i,0}$ *is distortion corresponding to the target quality, and* $P_{i,max}$ *is the maximum possible transmission power for the* i^{th} *user.*

The minimal power P_i^* satisfying the above requirements (1), (2), (3) when SINR constraints are met with equality, [7]. This results in

$$P_i^* = \frac{\sigma^2}{h_i\left(\frac{R_c}{R_i\gamma_i(R_i)}+1\right)\left(1-\sum_{j=1}^{N}\frac{1}{\frac{R_c}{R_j\gamma_j(R_j)}+1}\right)} \tag{4}$$

The minimal power P_i^* is feasible only if $0 < P_i^* \leq P_{i,max}$, which yields

$$\sum_{j=1}^{N}\frac{1}{\frac{R_c}{R_i\gamma_i(R_i)}+1} < 1 - \frac{\sigma^2}{\min_i\left[h_i P_{i,max}\left(\frac{R_c}{R_i\gamma_i(R_i)}+1\right)\right]} \tag{5}$$

When there is no maximum power constraint, the feasibility condition reduces to

$$\sum_{j=1}^{N}\frac{1}{\frac{R_c}{R_j\gamma_j(R_j)}+1} < 1 \tag{6}$$

Therefore, for given β_i, we can search through all possible R_i and find the pairs $(R_i,\ \gamma_i)$ that satisfy both the distortion constraint (3) and the feasibility conditions (i.e., (5) or (6)). For each feasible pairs, we determine the corresponding minimal power P_i^*. The combination that achieves the minimal P_i^* is the optimal $(R_i,\ \gamma_i)$ pair for the given β_i.

2) Quality factor q_i*:* Equation (4) indicates the minimal transmission power required for given $\mathbf{R_s}$ and corresponding $\boldsymbol{\Gamma}(\mathbf{R_s})$ that satisfies the quality requirement. We would like to find the pair $(\mathbf{R_s},\ \boldsymbol{\Gamma}(\mathbf{R_s}))$ that can lead to minimal transmission power at each user among all feasible $(R_i,\ \gamma_i)$ sets satisfying (3) and (5) or (6). Assume $(\mathbf{R_s},\ \boldsymbol{\Gamma}(\mathbf{R_s}))$ is one feasible set and P_i^* is the corresponding minimal transmission power at each user. Now consider another set $\tilde{\mathbf{R}}_\mathbf{s},\ \tilde{\boldsymbol{\Gamma}}(\mathbf{R_s})$ with corresponding $\tilde{P}_i^*$. When $\tilde{R}_{s,i}\tilde{\gamma}_i(\tilde{R}_i) \leq R_{s,i}\gamma_i(R_i)$, from (4) we observe that

1) $\{\tilde{R}_{s,i}, \tilde{\gamma}_i(\tilde{R}_{s,i})\}$ *is also feasible if* $\{R_{s,i}, \gamma_i(R_{s,i})\}$ *is feasible, and*
2) *The minimum power* $\tilde{P}_i^*$ *determined by* $\{\tilde{R}_{s,i},\ \tilde{\gamma}_i(\tilde{R}_i)\}$ *is less than that by* $\{R_{s,i},\ \gamma_i(R_i)\}$*, i.e.,* $\tilde{P}_i^* \leq P_i^*$*.*

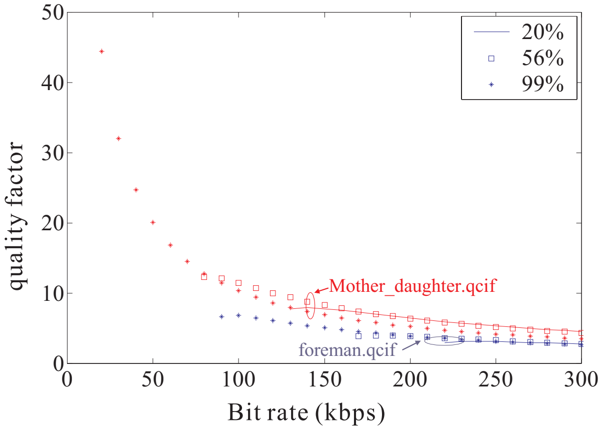

Fig. 3. Quality factor q_i for received distortion $D_{i,0} = 50$ at different INTER rates β_i for video sequences "mother_daughter.qcif" and "foreman.qcif".

TABLE I
SIMULATION PARAMETERS.

chip rate R_c	8.192 MHz
compression complexity β_i	{20, 56, 99}%
Maximum Distortion $D_{i,0}$	50

We see that $R_i\gamma_i(R_i)$ is an important parameter for our work and define

$$q_i = \frac{R_c}{R_i\gamma_i(R_i)} \tag{7}$$

as *quality factor*. The larger the quality factor is, the less the power is consumed for the same quality, or the higher the utility function is. Hence a larger q_i is preferred. The power ratio between using the largest quality factor $q_{i,max}$ and other q_i is

$$\frac{P_{i,min}}{P_i} = \frac{(q_i+1)\left(1-\sum_{j=1}^{N}\frac{1}{q_j+1}\right)}{(q_{i,max}+1)\left(1-\sum_{j=1}^{N}\frac{1}{q_{j,max}+1}\right)} \tag{8}$$

In Fig. 3 we show how the quality factor q_i changes as a function of bit rate when QCIF video sequences "mother_daughter.qcif" and "foreman.qcif" are compressed at different INTER rates for distortion constraint of $D_{i,0} = 50$ (this corresponds to PSNR = 31dB). The chip rate is set to $R_c = 8.192\times10^6$ chips/s as described in Table I. Stuhlmüller's models [8] are used to describe distortion from both lossy source compression and transmission errors. It shows that

1) q_i [1] *decreases as bit rate increases, given the INTER rate; and*
2) *The range of* q_i *is quite large. This provides an opportunity to reduce the transmission power significantly.*

Now we see that for each complexity, there exists a bit rate and a corresponding SINR achieving the maximum quality factor and consequently maximum utility. In other words, for

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[1] There is a small interval during which q_i stays about the same in the beginning part of the feasible rate range.

TABLE II

MAXIMUM QUALITY FACTORS AT DIFFERENT INTER RATES

INTER rate	"mother_daughter.qcif"			"foreman.qcif"		
	γ	R_s	q	γ	R_s	q
20%	7.35	140	7.95	10.79	240	3.16
56%	8.34	80	12.28	11.34	180	4.01
99%	9.22	20	44.40	11.96	100	6.85

TABLE III

NUMBER OF USERS.

INTER rates	20%	56%	99%
"mother_daughter.qcif" (slow-moving)	8	13	45
"foreman.qcif" (fast-moving)	4	5	7

certain video sequence, the optimal bit rate, SINR and quality factor are determined by the compression complexity. This simplicity is because we have the distortion constraint at each user, which constraints γ_i (equivalently P_i) given R_i. In the conventional power control problem, R_i and γ_i (or P_i) are two independent variables.

D. Maximizing Utility Over a Range of Complexity

We observe from Fig. 3 that the largest quality factor, $q_{i,max}$, occurs at the highest compression complexity. It is reasonable that the video encoder works at the highest possible complexity to reduce transmission power, in other words, larger utility is achieved at the expense of more compression computation. Since keeping working on a high complexity imposes a high volume of computation on the video compression and consumes a large amount of signal processing power, bound is set for compression complexity to prohibit the video encoder from draining too much battery. This complexity bound determines the optimal operating point. Such an algorithm is referred to as *a complexity-bounded power control method.*

E. Influence of Source Statistics

Different video sequences have different end-to-end distortion when compression algorithms and channel conditions are exactly the same. Fast-moving pictures require more bits for the same distortion than slow-moving pictures due to less correlation between adjacent video frames. In other words, for the same source compression algorithm, channel conditions and same video quality, minimum SINR requirements are different for different sequences for the same quality requirement, hence the transmission power is also different. It is clearly shown in Fig. 3 that the quality factor is larger for a slow-moving video sequence "mother_daughter.qcif" than for a fast-moving sequence "foreman.qcif". Since a higher q_i has the advantage of lowering transmission power P_i, a slow-moving video sequence consumes less transmission power than a fast-moving video sequence given the same desired end-to-end quality.

To summarize, we observe that when only transmission power is considered, the source encoder works at its largest quality factor $q_{i,max}$. Usually this forces the terminal to work with the highest possible complexity. The other two optimal parameters: the bit rate and required SINR are set to reach such $q_{i,max}$ while satisfying the feasibility criterion (which depends on other terminal's operating points). Hence this optimal pair for a video sequence is determined by the video characteristics, video codec and the modem, but is independent of path gain h_i. One way to implement this complexity-bounded algorithm would be the following: The central base station collects algorithms for the video codec when one terminal is admitted, and upon the change of video scene or after a predetermined period, $q_{i,max}$ is updated as well as bit rate and required SINR while satisfying the feasibility criterion. Then the required transmission power is computed from (4).

III. PERFORMANCE STUDY

An example system is used to examine the properties of our algorithm. We assume the same source compression algorithm (H.263 [5] in this paper) and the same compression complexity choice are used in all terminals. This can be true if video transmission is standardized for a certain application. Stuhlmüller's models [8] are used to describe distortion from both lossy source compression and transmission errors.

A. Number of users

It is important to know how many users can be accommodated in one cell. Not considering the constraint on maximum transmission power, from (6) we get the maximum number of users

$$N_{max} = \mathrm{argmax}_N \left\{ \sum_{j=1}^{N} \frac{1}{q_{j,max}+1} < 1 \right\} \qquad (9)$$

It is seen that to maximize the number of users we need select the maximum possible $q_{j,max}$ for all users, the same criterion as maximizing utility.

We first examine how many users of the same characteristics (either slow-moving or fast-moving, represented by "mother_daughter.qcif" and "foreman.qcif", respectively) can be supported simultaneously. Then we assume the video distributes evenly between fast-moving and slow-moving sequences. The choice of parameters is summarized in Table I. The capacity of the system is shown in Table III. It is clear that a system can accommodate more slow-moving video sequences than fast-moving ones.

B. Utility ratio

In this section, we try to analyze the system performance with N terminals. For simplicity, we assume the video sequences transmitted by all terminals have the same characteristics, and the complexity at all terminals is bounded by the same complexity, with a corresponding maximum quality factor q_{max}. We compare the gain from all terminals using q_{max} versus using some lower $q < q_{max}$.

From (4), the optimal utility function for the i^{th} user working at quality factor q is

$$U_i = \frac{f_r}{P_i^*} = \frac{h_i f_r}{\sigma^2}\left(q+1-N\right). \qquad (10)$$

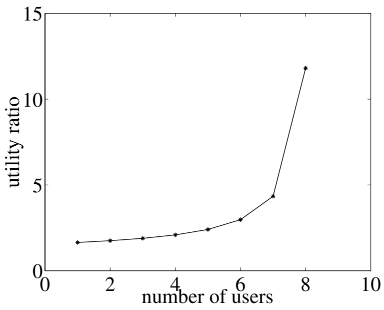

Fig. 4. Utility ratio between algorithms using q_{max} and q.

Equation (10) indicates that as more users enter the system, the utility of each user decreases. This is because higher transmission power must be used by each user to combat interference from others. For a fixed number of users, a terminal which is far away from the base station (with a small h_i), higher transmission power is required to achieve the same quality, and hence this user achieves lower utility than terminals that are closer (with larger h_i).

The ratio between utility functions by using q_{max} and other q is written as

$$\frac{U_{i,max}}{U_i} = \frac{q_{max} + 1 - N}{q + 1 - N}. \tag{11}$$

This ratio is an increasing function of number of users in one cell as described in Fig. 4. As the number of users approaches the limit of the system, the utility ratio becomes significant. This means that the power savings from using optimal operating point at each user (i.e. working at q_{max}) increases as the number of user increases.

C. Overall system utility

We define the overall system utility as the total number of frames transmitted per Joule of transmission power consumed by all the users. Assuming N users, this utility can be written as

$$U_{tot,N} = \frac{\sum_{i=1}^{N} f_r}{\sum_{i=1}^{N} P_i} = \frac{N f_r}{\sum_{i=1}^{N} \frac{Q_N}{h_i}} = \frac{f_r}{\sigma^2} \frac{N(q+1-N)}{\sum_{i=1}^{N} \frac{1}{h_i}} \tag{12}$$

where $Q_N = h_i P_i = \frac{\sigma^2}{q+1-N}$. For a fixed N, the total utility increases with q linearly, as in the case of single user utility. Hence when the number of users is given, the maximized overall system utility occurs at the highest quality factor q_{max}. At follows, we let the system work at q_{max} to maximize utility. However, the overall utility is not necessarily an monotonic function of the number of users in the system. To observe how this term varies with the number of users, we look at

$$\begin{aligned} \frac{U_{tot,N}}{U_{tot,N-1}} &= \frac{N}{N-1} \frac{q_{max} + 1 - N}{q_{max} + 2 - N} \frac{\sum_{i=1}^{N-1} \frac{1}{h_i}}{\sum_{i=1}^{N} \frac{1}{h_i}} \qquad (13) \\ &= \left[1 + \frac{q_{max} - 2(N-1)}{(N-1)(q_{max} + 2 - N)}\right] \left(1 - \frac{\frac{1}{h_N}}{\sum_{i=1}^{N} \frac{1}{h_i}}\right) \end{aligned}$$

Overall system utility can be used to decide whether to admit a new user. In order to improve system utility by addition of one user we need $\frac{U_{tot,N}}{U_{tot,N-1}} \geq 1$, which results in $q_{max} - 2(N-1) \geq 0$, or $N \leq \frac{q_{max}}{2} + 1 \approx \frac{N_{max}}{2}$, i.e., the number of users should not exceed half of the capacity to get a maximized total utility.

IV. DISCUSSION

In this work, we propose an algorithm that determines the video encoder bit rate and received SINR to maximize the number of received picture frames per Joule, or to minimize transmission power in a CDMA cell, under a certain quality constraint. We find that these parameters depend on algorithms used in video codec, modem and the characteristics of video scene under transmission.For each possible compression complexity, there is a unique optimal operating point. When there exists multiple choices of complexity, a video encoder is usually forced to work on the highest complexity. This is reasonable since the minimized transmission power comes at the expense of a high volume of computation on the video codec and a large amount of compression power. To prohibit the video encoder from draining too much battery, we set bound for compression complexity. This complexity bound determines the optimal operating point. Thus, we refer to the developed algorithm "a complexity-controlled power control method". Capacity and utility function are studied by an example system. We show that using the optimal operating point can improve the utility of individual terminals significantly compared to using non-optimal operating points, especially when the number of terminals is large.

When compression power consumption is also taken into consideration, we can determine the optimal operating point that minimizes the sum of the transmission and compression power consumption by searching in the complexity space instead of the space of {bit rate, complexity, SINR}. This is a very nice property, especially when a large number of users are in the system. This work is in progress.

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