

An Efficient Adaptive FEC Algorithm for Short-Term Quality Control in Wireless Networks

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Abstract—In error-prone wireless networks, packet errors causes media quality degradation. To enhance media quality in case of packet errors, Forward Error Correction (FEC) mechanisms are the preferred error-control schemes for interactive multimedia applications. However, random error behavior causes unstable media quality so that average quality is not a sufficient metric to represent media quality. In this paper, we first propose a novel short-term quality metric to represent the short-term media quality. Second, based on this metric, we develop adaptive FEC mechanisms to determine appropriate FEC redundancy to protect media packets under various wireless error models. Simulation results show that the proposed adaptive FEC mechanisms tolerate most of burst errors to meet the user requirements on media quality with appropriate bandwidth consumption.

Keywords—short term Quality; adaptive FEC; error control;

I. INTRODUCTION

The main challenge of multimedia transmission over wireless networks is the unpredicted and time-varying channel conditions due to fading, interference, and mobility. The error-prone characteristics of wireless channel cause quality degradation of multimedia services. To reduce the effects of wireless errors, Forward Error Correction (FEC) is an attractive alternative to Automatic Repeat reQuest (ARQ) for providing reliability without increasing too much latency. However, FEC mechanisms introduce extra bandwidth overhead. Hence, the compromise of bandwidth utilization and video quality becomes an important issue.

FEC mechanisms transmit additional redundant information to repair lost packets. Based on the types of redundant information, FEC mechanisms can be divided into two categories: *media independent* and *media specific* FEC schemes [1]. Media specific FEC schemes encode multimedia content by different bit-rate codecs and piggyback them into consequent packets [2]. When the primary packet is lost, the lower-quality one is used to replace it. Media specific FEC schemes provide less bandwidth but causes higher decoder complexity and lower recovery quality. Media independent FEC uses block codes (e.g. Reed-Solomon or parity codes) to provide redundant information. Media independent FEC can

be implemented at different levels from byte level to packet level [3]. The byte-level and packet-level FEC schemes define a symbol in unit of a byte and a packet, respectively. A byte-level FEC scheme provides small-scale error protection and achieves better reliability than a packet-level one in Gaussian noise channel [4]. However, slow fading in wireless channel brings dependent relations of lost packets and alleviates the recovery capabilities of byte-level FEC so that there is a need for additional packet-level protection to increase the reliability of multimedia communication [5]. In this paper, we consider the quality degradation caused by different network error models, so the packet level case of media independent FEC is studied.

There have been many research efforts in providing adaptive FEC mechanisms to protect multimedia packets in error-prone networks [3][6][7][8]. FEC mechanisms produce additional redundant packets and reduce bandwidth utilization. Hence, the compromise of bandwidth utilization and media quality becomes an important issue of FEC algorithms. J. Feng et al. [6] introduce an adaptive FEC algorithm which maximizes total frame quality for MPEG streams and bandwidth utilization ratio. FEC algorithms proposed by A. Moid et al. [7] select an appropriate number of FEC packets to minimize the video distortion without overloading the network. C. Boutremans et al. [8] introduce E-Model [9] to select the number of FEC packets to maximize voice quality under the TCP-Friendly rate control mechanisms [10]. To predict the recovery packet error rate (PER), these studies assume that the correlation structure of the error process can be modeled with low order Markov chains and adjust redundant information based on network estimation. These studies have good performance in average quality. However, in time-varying environment, average quality fails to capture short-term media quality especially when the relation between lost packets is dependent. The average quality filters out the variation of quality and ignores the behavior of short-term quality. Hence, in this paper, we propose a novel quality metric to assess short-term quality (short as SQ). Furthermore, according to the SQ metric, we propose adaptive FEC mechanisms to provide appropriate protection for packets. The simulation

results show that our FEC mechanisms not only avoid most of burst errors but also save bandwidth by selecting appropriate amount of redundancy.

This paper is organized as follows: In Section II, we describe the problem of FEC mechanisms based on the average quality metric and propose a metric for short-term quality. In section III, adaptive FEC mechanisms with the short-term quality metric are proposed for various wireless error models. In Section IV, we simulate proposed mechanisms and compare them with some traditional FEC mechanisms. Finally, we conclude in Section V.

II. PROBLEM FORMULATION

High PER seriously degrades media quality in multimedia applications and adaptive FEC mechanisms aim to alleviate the influence of packet errors. Conventionally, the typical steps of FEC schemes are as follows [2][5][7][8]:

Step1: The transmitter collects feedback information from a receiver by ACK or RTCP packets [11].

Step2: The transmitter uses one of Maximum Likelihood Estimator (MLE) and Exponential Weighted Moving Average (EWMA) algorithms to smooth the observed PER.

Step3: Finally, the transmitter selects an appropriate FEC solution (i.e. n and k) to maximize the media quality or achieve a target PER calculated by the predefined recovery error function.

However, the estimated error rate cannot represent the random and dynamic error behavior explicitly. Figure 1 shows the dynamics of PER before and after FEC recovery in the case of Gaussian noise channel [12] with $PER = 0.1$ and target $PER = 0.05$. Although the average PER is within expected range, the PER during some short period is worse than user-tolerance though FEC is used. The voice quality even gets worse when packet error behavior approximates Gilbert Error Model or higher order Markov chain [13]. Hence, adaptive FEC mechanisms must take the dynamics of error rate into account. For the goal, we first define a new quality metric, called as SQ, to represent the media quality of T seconds or N packets. The value of T or N depends on human psychology. The existing voice quality measurement process [14] selects the standard 8-second samples or 400 20ms-packets for the quality estimation. ITU-R recommends limiting the duration of image sequences for subjective assessment to less than 10s [15]. For simplicity, we ignore the dependence of media quality called recency effects described in [16]; it means that SQ is independent of each other.

Based on SQ, we model the dynamics of packet errors by the probability that short-term quality SQ is worse than user-satisfactory quality Q_i , denoted as $\Pr\{SQ < Q_i\}$. For voice, according to [17], the codec types, PER and end-to-end delay primarily affect voice quality. For image and video, the reconstructed video quality distortion is obtained as the sum of the codec distortion and network error distortion. Codec distortion is the distortion due to video compression. It is the function of source rate. Network error distortion is a function

of the packet error rate. In this paper, we focus on the effects of packet errors on media quality. We assume that the codec and delay impairment for media quality is constant. It is reasonable when we use the constant codec rate and limit the maximum number n of FEC candidates to avoid excessive end-to-end delay. Hence, the objective of FEC recovery can be translated to $\Pr\{p_i < P_i\}$ where p_i is the observed PER in each N -packets after FEC recovery and P_i is a target error rate derived from Q_i . In this paper, we call $\Pr\{p_i < P_i\}$ *SQ violation probability*. The target error rate depends on the user's expectation. Codecs with concealment techniques conceals some degrees of packet errors but fail when PER is larger than a threshold PER_{max} [2]. Therefore, the P_i must be smaller than PER_{max} . If the used codec does not support concealment techniques, the existing voice quality measurement, such as E-Model [11], can be also used to obtain P_i . For video, the distortion matrix consisting of the reconstruction distortion values for video frames is used to acquire a proper value of P_i [18][19]. I, B and P frames have various levels of significance so FEC algorithms should assign different P_i for unequal error protection [20].

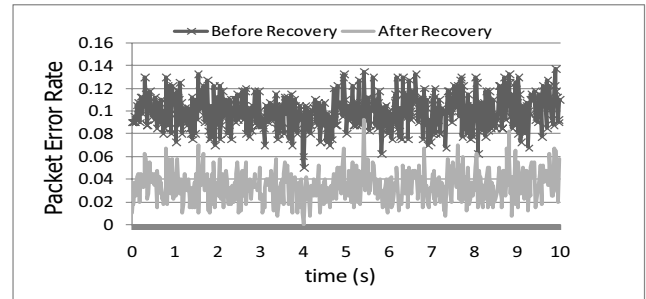


Figure 1. The dynamics of error behavior.

For adaptive FEC mechanisms, forcing the SQ violation probability close to zero will cost a large portion of bandwidth. By the fact that a user is also able to bear some degree of SQ violation probability, we define the objective function for adaptive FEC mechanisms as $\Pr\{p_i < P_i\} < \alpha$, where α is a user-defined threshold. The smaller value of α is, the higher media quality user obtains. We do not discuss the relation between the threshold and media quality because there should be more psychological experiment involved to verify. However, with no doubt, lower PER leads to better media quality.

III. AN EFFICIENT ADAPTIVE FEC ALGORITHM FOR SHORT-TERM QUALITY CONTROL

In this section, we present an adaptive FEC mechanism which adopts the proposed SQ to derive an appropriate FEC solution with respect to various error models and to achieve the user satisfactory quality.

A. Wireless Error Models

The variation of PER depends on the network characteristics. There have been many researches devoted to model the characteristics of wireless channel [12]-[13]. Specifically, they modeled the packet error behavior by

Markov Model with few states. Among them, two models in common are the Bernoulli Error Model in Gaussian noise channel and the Gilbert Error Model in Rayleigh fading channel. Bernoulli error model represents the independence between two error packets and Gilbert Error Model addresses the error bursting nature in networks. There are also many different error models discussed, but for simplicity we also propose an adaptive FEC mechanism for unknown Error Model.

In Bernoulli Error Model, the error events characterized by random variable X is independent and identically distributed (i.i.d) and the probability mass function of X is given by

$$P\{X\} = \begin{cases} 1-p & X=0 \\ p & X=1 \end{cases} \quad (1)$$

where $X=1$ represents that a packet is error and $X=0$ represents error-free transmission. The parameter p is PER and can be statistically estimated from a sample of sequence by

$$\hat{p} = n_1 / N \quad (2)$$

where n_1 is the number of packet errors in the sequence of N samples.

In Gilbert Error Model, the error events are modeled as a discrete-time Markov chain with two states shown in Figure 2. In state 1, each packet is lost and in state 0, the transmission is error free. The maximum likelihood estimators of p and q for a sample sequence are

$$\hat{p} = n_{01} / n_0, \quad \hat{q} = n_{10} / n_1 \quad (3)$$

where n_{10} is the number of transitions from 1 to 0 and n_{01} is the number of transitions from 0 to 1. In the event sequence, n_0 is the number of 0s and n_1 is the number of 1s.

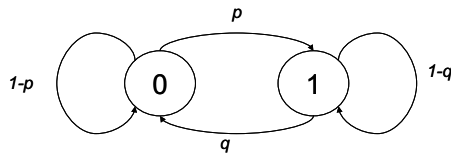


Figure 2. The Gilbert model. State 0 represents an error-free transmission. In state 1, each packet is lost.

B. Error Control for Bernoulli Error Model

The goal of our adaptive FEC mechanisms is to select an appropriate FEC solution, which satisfies the condition, $\Pr\{p_i < P_t\} < \alpha$. First, we consider a population of items which approximates a Bernoulli Error Model with probability p . If N items are tested to determine the short-term quality, we determine the confidence interval for short-term PER, $\hat{p}_N$, as follows. Let Y denote the number of error packets in N Bernoulli samples, and then Y is a binomial random variable with parameters n and p . So we have $\hat{p}_N = Y / N$. According to De Moivre-Laplace theorem, Y is normally distributed with mean Np and variance $Np(1-p)$. Hence,

$$\frac{Y - Np}{\sqrt{Np(1-p)}} \sim N(0,1) \quad (4)$$

which $\sim$ means “is approximately distributed as” and $N(0,1)$ is a standard normal distribution. Therefore, for any $\alpha \in (0,1)$, we can obtain the confidence interval of Y by

$$\Pr\left\{\frac{Y - Np}{\sqrt{Np(1-p)}} < z_\alpha\right\} \approx 1 - \alpha$$

where z_α is z-score.

Based on $\hat{p}_N = Y / N$, we obtain

$$\hat{p}_N < p + z_\alpha \sqrt{\frac{p(1-p)}{N}} \quad (5)$$

For Reed Solomon FEC, the PER after recovery, p_a , is calculated by

$$p_a = f(n, k, p) = p \left(1 - \sum_{i=k}^{n-1} \binom{n}{i} (1-p)^i p^{n-1-i}\right) \quad (6)$$

From the above, we summarize the FEC algorithm for Bernoulli Error Model in Figure 3. In Figure 3, a solution table contains candidate FEC solutions (n, k) . Whenever the lost sequence (LS) of N packets are gathered, the receiver calculates the short-term PER and updates the Bernoulli parameter p by the EWMA or average algorithm in step 1.

Input: a FEC solution table Γ
 When gathering the LS of N packets, do
 Update the Bernoulli parameter p by the average algorithm.

1. $\hat{p}_N = p + z_\alpha \sqrt{p(1-p)/N}$
2. $S = \text{NULL}$
3. For each (n, k) in Γ
 $p_a = f(n, k, \hat{p}_N)$
 if $(p_a < P_t)$
 $S = S \cup (n, k)$
4. Find the set T which n/k is minimum in S
5. Select (n, k) which n is minimum in T
6. Select the codec i which $r_i * n/k < R$

Figure 3. Adaptive FEC mechanism for Bernoulli Error Model.

According to (5) and (6), we obtain the set S where the FEC solutions have ability to reduce PER lower than tolerant range in step 4. In step 5, the FEC solutions which use the minimum bandwidth are selected to the set T . In step 6, our mechanism chooses the FEC solution which n is the smallest in T to minimize recovery delay. Finally, in step 7, the choice of codec should be constrained by TCP-Friendly Rate Control (TFRC) to keep network fairness [9] where R is maximum sending rate from TFRC and r_i is the encoding rate when the codec i is used.

C. Error Control for Gilbert Error Model

Packet errors over Gilbert Model can be a renewal error process [14]. The lengths of consecutive inter-error intervals (also called gaps) are i.i.d. Following the development of [14], let $g(i)$ denote a gap length $i-1$, i.e. $g(i) = \Pr\{0^{i-1}1|1\}$, where ‘1’ denotes a lost packet and 0^{i-1} denotes consecutive $i-1$ packets successfully received. Similarly, let $G(i)$ denote the probability that a gap length is greater than $i-1$, i.e., $G(i) =$

$\Pr\{0^{i-1}|1\}$. Then we denote the probability $R(m, n)$ that $m-1$ packet errors in the following $n-1$ packets and it can be computed by recurrence. Thus,

$$R(m, n) = \begin{cases} G(n) & \text{for } m=1 \text{ and } n \geq 1 \\ \sum_{i=1}^{n-m+1} g(i)R(m-1, n-i) & \text{for } 2 \leq m \leq n \end{cases} \quad (7)$$

where

$$G(i) = \begin{cases} 1 & \text{if } i=1 \\ q(1-p)^{i-2} & \text{otherwise} \end{cases} \quad (8)$$

$$g(i) = \begin{cases} 1-q & \text{if } i=1 \\ q(1-p)^{i-2}p & \text{otherwise} \end{cases} \quad (9)$$

Based on $R(m, n)$, we have the probability p_a that a packet is recovered by Reed Solomon FEC by

$$p_a = f_2(n, k, p, q) = \frac{1}{k} \sum_{i=1}^k \left(\frac{p}{p+q} - P_{REC}(i) \right) \quad (10)$$

with

$$P_{REC}(i) = \sum_{l=1}^{n-k} \sum_{m=0}^{\min(i-1, l-1)} P_B R(m+1, i) R(l-m, n-i+1) \quad (11)$$

where $P_B = p/(p+q)$ and $P_{REC}(i)$ represents the probability that the i -th packet is lost but recovered by using the Reed-Solomon FEC RS(n, k). For a renewal error process, since the FEC blocks are independent and identically distributed, we regard each FEC block as a Bernoulli random variable with probability p_a . In this paper, FEC parity data is piggybacked into consequent packets; it means N/k FEC blocks are in N packets. Therefore, N packets in Gilbert Error Model translate to N/k FEC blocks in Bernoulli Error Model. Based on (5), we obtain

$$\hat{p}_N < p_a + z_\alpha \sqrt{\frac{p_a(1-p_a)}{(N/k)}} \quad (12)$$

We summarize the FEC mechanism for Gilbert Error Model in Figure 4 which has the similar idea as Figure 3.

D. Error Control for Unknown Error Model

In an unknown error model, a receiver records short-term PER p_i and LS of the N packets by a sliding window of size W . Suppose that the past W short-term PERs in the sliding window is $\hat{p}^{i-W+1}, \hat{p}^{i-W+2}, \dots, \hat{p}^i$ and its sorted version is simply denoted as $P^1, P^2, \dots, P^W$, where $P^1 \leq P^2 \leq \dots \leq P^W$. The probability that short-term PER, $\hat{p}_N$, is not greater than P^r can be obtained by

$$F(P^r) = P(\hat{p}_N \leq P^r), r=1, 2, \dots, W \quad (13)$$

We assume that the order statistics is uniform distributed and the expectation of $F(P^r)$

$$E(F(P^r)) = \frac{r}{W+1}, r=1, 2, \dots, W \quad (14)$$

Input: a FEC solution table Γ

When gathering the LS of N packets, do

1. Estimate Gilbert parameter $\hat{p}$ and $\hat{q}$
2. $S = \text{NULL}$
3. For each (n_j, k_j) in Γ

$$p_a = f_2(n_j, k_j, \hat{p}, \hat{q})$$

$$\hat{p}_N = p_a + z_\alpha \sqrt{p_a(1-p_a)/(N/k)}$$

if ($\hat{p}_N < P_t$)

$$S = S \cup (n_j, k_j)$$
4. Find the set T which n_j / k_j is minimum in S
5. Select (n, k) which n is minimum in T
6. Select the codec i which $r_i * n/k < R$

Figure 4. Adaptive FEC mechanism for Gilbert Error Model.

Input: a FEC solution table Γ

When gathering the LS of N packets, do

1. Record the new LS_1
2. n_1 = the number of lost packets in LS_1
3. $p_1 = n_1/N$ and insert p_1 into the sliding window of size W .
4. Select the r -th order statistics p^r and its loss sequence LS_r .
5. $S = \text{NULL}$
6. For each (n_j, k_j) in Γ

$$LS_{r'} = LS \text{ recovered from } LS_r \text{ by } (n_j, k_j)$$

$$n_1' = \text{the number of lost packets in } LS_{r'}$$

$$p_a = n_1'/N$$

if ($p_a < P_t$)

$$S = S \cup (n_j, k_j)$$
7. Find the set T which n_j / k_j is minimum in S
8. Select (n, k) which n is minimum in T
9. Select the codec i which $r_i * n/k < R$

Figure 5. Adaptive FEC mechanism for unknown error model.

Then, given a threshold α , the order index is obtained by $\hat{r} = \lfloor (W+1)(1-\alpha) \rfloor$. However, due to the lack of the error relation between packets, it is impossible to find the close form of the recovery PER. Hence, we use a heuristic method to find an appropriate FEC solution. If the r -th order statistics in sliding window is selected, the loss sequence in the r -th order statistics, LS_r , is used to select the FEC solutions which can alleviate the PER of LS_r within target PER, P_t . We summarize the FEC mechanism for unknown error model in Figure 5.

By using a larger window size W , it is possible to estimate the PER more accurately. However, it causes the window-based estimator responds more slowly to the dynamics of network errors. Hence, the determination of W is subject to trade-off between accuracy and response time.

IV. SIMULATION RESULTS

We implement and test our adaptive FEC mechanisms with SQ (AFEC-SQ) in NS2 simulator [21]. In the simulations, two types of error models are used: (1) Bernoulli Error Model, (2) Gilbert Error Model. In whole simulations, $N = 400$, the threshold α is set to 0.05 and the target error rate P_t is set to 0.02. The supported FEC solutions are listed in Table 2. The FEC solutions are sorted by n/k and the maximum value of n is set to 6 to avoid excessive end-to-end delay.

TABLE 2. THE SUPPORTED FEC SOLUTION TABLE.

No.	FEC
1	RS(1,1)
2	RS(5,4)
3	RS(4,3)
4	RS(3,2)
5	RS(5,3)
6	RS(4,2)
7	RS(6,3)
8	RS(5,2)

Figure 6 shows the behavior of different adaptive FEC mechanisms, AFEC-SQ and AFEC-Avg in Bernoulli Error Model (abbreviated as “B”) with the probability, p . The range of p in this simulation is from 0.01 to 0.2. AFEC-Avg adjusts a FEC solution by only considering whether p_a in (6) or (10) is smaller than P_t . In Figure 6, the SQ violation probability is $\Pr\{p_i < P_t\}$ and AFEC-SQ (B) is the mechanism described in Figure 3. When the network PER is 0.04, AFEC-Avg considers that the network error rate is lower than the target error rate, and uses no FEC protection. However, in fact, the random error behavior results in the SQ violation probability 0.1. AFEC-SQ is aware of this situation and chooses the next level of FEC solution to protect packets shown in Figure 7. Hence, under the SQ consideration, AFEC-SQ selects more appropriate redundancy than AFEC-Avg.

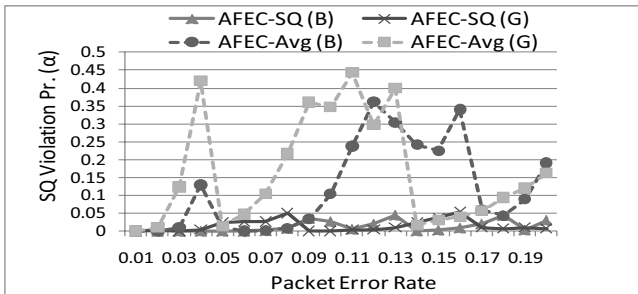


Figure 6. the performance comparison between AFEC-SQ and AFEC-Avg in Bernoulli Error Model with $p=0.01\sim 0.2$ and Gilbert Error Model with $q=0.8$ and $p = 0.01\sim 0.2$.

Figure 6 also compares AFEC-SQ and AFEC-Avg in Gilbert Error Model (abbreviated “G”) with $q = 0.8$ and p ranges from 0.01 to 0.2. AFEC-SQ (G) is the mechanism described in Figure 4. The recovery PER of AFEC-Avg in Gilbert Error Model is calculated by (11). As illustrated in Figure 6 and Figure 7, AFEC-Avg in Gilbert Error Model causes more serious SQ violation probability than that in Bernoulli Error Model. For examples, when p is equal to 0.04, AFEC-Avg exploits no FEC protection and results in the SQ violation probability almost 0.45 that is much higher than that in Bernoulli Error Model. Hence, under bursting error environment, it is more essential for adaptive FEC

mechanisms to consider short-term quality. The figures also represents that AFEC-SQ under Gilbert Error Model also achieves the expected SQ violation probability.

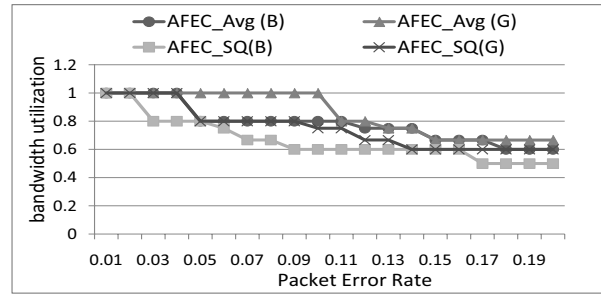


Figure 7. Bandwidth utilization of AFEC-SQ and AFEC-Avg in Bernoulli Error Model with $p=0.01\sim 0.2$ and Gilbert Error Model with $q=0.8$ and $p = 0.01\sim 0.2$.

Figure 8 shows the performance of AFEC-SQ with order statistics in Bernoulli and Gilbert Error models. AFEC-SQ (order stat. in B or G) is the mechanism described in Figure 5 under Bernoulli or Gilbert Error Model. Simulation results show that when $W < 30$, the AFEC-SQ dramatically changes the selection of FEC solutions and causes high delay variation. Hence, in the following simulation, W is set to 50. The SQ violation probability of AFEC-SQ with order statistics is slightly over the threshold, 0.05. The inaccuracy comes from the nature of window-based estimator. The simulation results also show that AFEC-SQ with order statistics is capable of achieving the threshold under unknown error behavior.

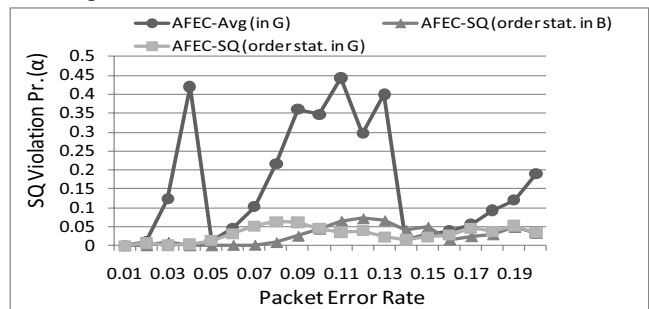


Figure 8. the comparison of order statistics in Bernoulli and Gilbert Error Model with $q=0.8$ and p is 0.01~0.2.

Figure 9 compares the performance of AFEC-SQ in Bernoulli and Gilbert Error Model. Under different value of α , the maximum SQ violation probability is found under the range, $0.01 \leq p \leq 0.2$ for Bernoulli and Gilbert Error Model with $q = 0.8$. This figure shows that the maximum SQ violation probability approximates to the threshold in the control of AFEC-SQ with Bernoulli or Gilbert upper bound. Although AFEC-SQ does not fit the threshold well due to the discrete property of the FEC solution table, the control is still effective.

Figure 10 represents the bandwidth utilization for AFEC-optimal [8] and AFEC-SQ in Bernoulli and Gilbert Error models. AFEC-optimal chooses a FEC solution by maximizing the E-Model utility function. This figure shows that AFEC-optimal uses higher bandwidth than AFEC-SQ where both mechanisms achieve user-satisfactory quality. This figure also compares various AFEC-SQ mechanisms. The results show that AFEC-SQ with order statistics uses lower

FEC solution no. than AFEC-SQ (B) and AFEC-SQ (G). The main reason is that "AFEC-SQ (order stat. in B or G)" dynamically adjusts FEC solution no. when the observed error rate in sliding window is lower. AFEC-SQ (B or G) selects the FEC solution based on the parameters of error models observed by the average algorithm but it obtains lower SQ violation as shown in Figure 8. This effect comes from the dynamic adjustment of AFEC-SQ with order statistics by the observation of sliding window and can be alleviated by using the EWMA algorithm for AFEC-SQ (B).

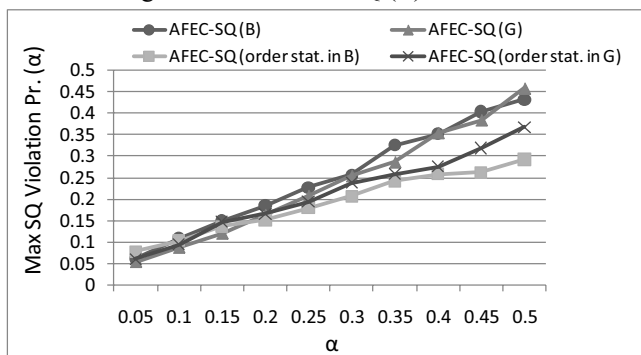


Figure 9. AFEC-SQ in various alpha values.

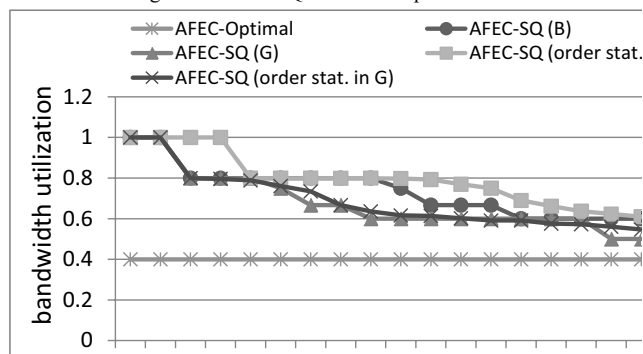


Figure 10. Bandwidth utilization for various mechanisms.

V. CONCLUSIONS

The dynamics of packet error rate results in unstable quality. In this paper, we propose a new quality measurement approach to evaluate the effect of unstable media quality and AFEC-SQ to select an appropriate FEC solution to alleviate the uncertainty. In the simulation results, the proposed AFEC-SQ meets the objective function very well and SQ estimates short-term quality more accurately than average in the AFEC-Avg. AFEC-SQ also occupies less bandwidth than AFEC-Optimal while providing near the same quality.

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