Delay analysis of Block Coding over a Noisy Channel with Limited Feedback

Raghava N. Swamy and Tara Javidi
Department of ECE
UCSD, La Jolla CA - 92092
raghava@ucsd.edu, tjavidi@ucsd.edu

***Abstract*—This work analyzes the average delay performance of block coding schemes when the arrival stream is stochastic. From classical Shannon Theory, it is known that communication is feasible at all rates strictly below capacity of a channel. However, this reliable scheme of communication is realized with unbounded coding length and hence average delay. This work considers the delay analysis of general block coding schemes over a noisy channel in presence of retransmission requests. Modeling the communication system as a queuing system with bulk service, an expected delay analysis is provided. The expected delay bits experience is then optimized by an appropriate choice of forward error correction scheme.**

I. Introduction

This work analyzes the average delay performance of a block coded communication system where information bits arrive stochastically and are delivered over a wireless channel in the presence of request for retransmission.

In the above setting, there are two important parameters of interest, the first critical performance measure is the probability that bits are erroneously decoded; the second measure of interest is the delay experienced by the information bits defined as the interval between bit arrival and decoding time. Shannon's classical results give the maximum data rate attainable for reliable communication (with vanishing probability of error) over a noisy channel using asymptotically long block coding (a.k.a forward error correction), while Gallager's error exponents ([14]) give exponentially decaying upper bounds on the probability of block error as functions of the block length. However, in a system where bit/packets of information arrive stochastically, the choice of asymptotically large block length compromises the timely delivery of bits. In other words, longer length block codes guarantee a more reliable delivery of information only at the cost of long delays associated with the bits waiting time in a transmission buffer (queuing delay). A similar tradeoff exists in the choice of coding rate and the error exponent; when the arrival rate is strictly below channel capacity, lower coding rate guarantees a reliable delivery but causes a tardy delivery of information. This paper analyzes the average delay experienced by a bit as a function of the block coding length and rate. This analysis is then used to address the "optimal" (in average bit delay sense) choice of block coding length and rate.

Historically, the issue of delay sensitivity of bursty (stochastic) traffic has not received adequate attention in communication literature. Ephremedis and Hajek, in their paper aptly titled *Information theory and Communication networks: An Unconsummated Union* ([5]) brought attention to the importance of a unifying approach to information/coding and queuing theories. Fortunately, in recent years, there has been significant progress towards delay analysis in the context of communication over fading channels. Under asymptotic (large or small) delay scenarios, and in the presence of channel state information at the transmitter, Berry and Gallager ([10]) studied the trade-off between energy and delay. In [7], Negi and Goel obtained a joint "QoS exponent" for a fading channel with CSI available at the transmitter and using a streaming code. In [6], Kittipiyakul, Elia and Javidi looked at the probability of delay violation as well as decoding error in a high SNR asymptotic in the absence of CSI at the transmitter. Cao and Yeh in [11] and Bettesh and Shamai in [8] used the dynamic programming approach to address the delay-power trade-off for block fading channels.

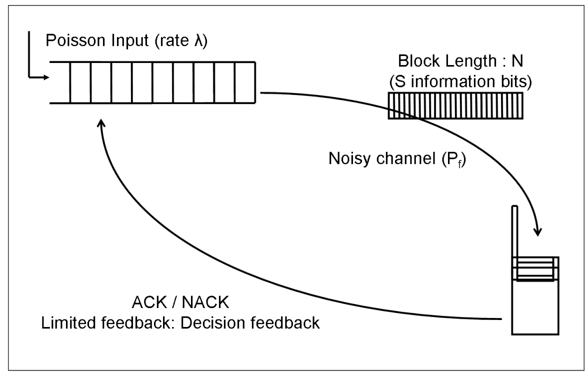

Fig. 1. System Model

The present paper is most closely related to [4], where the delay performance of block coding schemes over discrete memoryless channels is investigated. In [4], Dunn and Laneman consider the particular case of transmission over a binary erasure channel, while incorporating the information theoretic bounds for the overhead of varying code length/rate, and produce an achievable rate-delay trade-off region. In this paper, we consider the general problem of estimating the average bit delay of a given block coding scheme over a noisy channel where channel coding is also required to provide error detection. We model the overall system as a queue with bulk service and provide its delay analysis. Furthermore, we prove the existence of an optimal coding rate and length which minimizes the average bit delay. We later compute approximations to these quantities and show performance gains.

Similar to [4] and [8], we consider schemes which have acknowledgment in the form of a request for retransmission. Our approach can be viewed as providing insights into an optimal choice of time diversity in the context of Poisson delay sensitive traffic. We note that unlike [9] our notion of delay includes the queuing delay and accounts for randomness in the inter-arrival times of bits.

Before we close this section, we note that despite little attention paid to bulk-service queues in communication literature, our work is similar to [12] where a bulk-service model is used to analyze delay in random network coding.

This paper is organized as follows : Section II describes the model and formulation, Section III gives the queuing analysis, Section IV describes the optimization problem and Section V shows the application of our results to a memoryless binary symmetric channel (BSC). Finally, Section VI concludes the paper.

II. Problem Description

We consider the following communication scenario over a time slotted memoryless noisy channel using block coding: bits of information arrive at the transmitter according to a Poisson process with an average of λ bit arrivals per slot. Bits are queued in a buffer awaiting their encoding and transmission through the noisy channel (Fig. 1). The coding/transmission scheme is defined as follows: every N time slots, one of the two actions are taken:

1) Encoding and transmission of a newly formed codeword upon reception of an ACK from the receiver.
2) Re-transmission of a previously coded set of bits upon receipt of a NACK from the receiver.

An encoder-decoder pair $(\mathcal{F},\mathcal{D})$ is defined as mappings $\mathcal{F}:\mathcal{A}^S\rightarrow\mathcal{B}^N$ and $\mathcal{D}:\mathcal{B}^N\rightarrow[\mathcal{A}^S\cup\mathcal{R}]$, where $S\in\mathbb{N}^+$ represents the number of information bits in a code word, $N\in\mathbb{N}^+$ represents the block length of the code, $\mathcal{A}=[0,1]$, $\mathcal{B}$ is the channel alphabet and $\mathcal{R}$ is defined as the event of a *Detected Error*. The code rate r is defined as S/N bits per time slot. The noisy channel is characterized by its probability of symbol transmission failure $P_{\mathrm{f}}{=}P(\tilde{y}_j\neq y_j)$, where $y_j,\tilde{y}_j\in\mathcal{B}$ are the input and the output channel symbols respectively. The decoder $\mathcal{D}$ maps the detected block of symbols to either a codeword or a *Detected Error* event. An *Undetected Error* ($\mathcal{E}$) is defined as the event when the decoded codeword is different from the encoded one. Define P_{u} and P to be the probabilities of events $\mathcal{E}$ and $\mathcal{R}$ respectively.

During encoding, in the event that the number of queued bits is less than S, the transmitter pads the current content of the queue with zeros to make the total S and then encodes them as described above. In this case, it is assumed that the decoder has perfect knowledge of the number of bits encoded[1].

[1]The information contained in the "number of bits" is of the order of $log(S)$ and is negligible compared to S at large S

Consider the i^{th} information bit b_i. Let $T_{a,i}$ be the time the bit arrived at the transmitter. Let $T_{d,i}$ be the time the codeword containing information bit b_i was decoded to a codeword (either correctly or incorrectly) at the receiver. The delay for bit b_i, D_i is defined as $T_{d,i}-T_{a,i}$ and the average delay is defined as $\bar{D}=E[D_i]$.

The first contribution of our paper provides an average delay analysis for a given encoding/decoding scheme, i.e.

Objective I: Given an encoder-decoder pair $(\mathcal{F},\mathcal{D})$ with probability of detected error P and a request for retransmission mechanism, compute the expected bit delay ($\bar{D}$) for a stream of Poisson arrivals.

The second contribution of the problem concerns the "optimal" choice of coding scheme. Let ($\mathbb{F}_\beta$, $\mathbb{D}_\beta$) be the class of allowable encoder-decoder pairs, i.e. an arbitrary class of encoder-decoder pairs with an acceptable undetected error probability $P_u\leq\beta$, (β is a small constant). For instance ($\mathbb{F}_\beta$, $\mathbb{D}_\beta$) may represent the class of Reed-Solomon codes with $P_{\mathrm{u}}\leq\beta$. Given the traffic statistics, it is our goal to optimize the choice of the encoder-decoder pair $(\mathcal{F},\mathcal{D})\in(\mathbb{F}_\beta,\mathbb{D}_\beta)$. In other words,

Objective II: Find an optimal $(\mathcal{F}^*,\mathcal{D}^*)$, such that

$$E(\text{Delay}|\mathcal{F}^*,\mathcal{D}^*)\leq E(\text{Delay}|\mathcal{F},\mathcal{D})\qquad\forall(\mathcal{F},\mathcal{D})\in(\mathbb{F}_\beta,\mathbb{D}_\beta)\tag{1}$$

We can analyze the average delay experienced by each bit via a class of queuing models known as bulk service queues. Bulk service queues have been studied in transportation and operations research literature ([1],[2],[3]). We will specialize the bulk-service queuing system analysis to a Geometric service distribution with Poisson arrivals. Bulk service queuing systems have traditionally known to be hard to analyze due to the complexity of finding the roots of an associated characteristic equation ([2],[3]). We use efficient algorithms developed in [2] to solve for the numerical roots and hence get exact results for average delay. We also provide upper and lower bounds which provide insight when addressing our second objective. We assume that the computation time for encoding and decoding is negligible. In Section III, we outline this queuing model and its analysis.

III. Expected Delay Analysis

Given a Poisson arrival of bits and a block coding scheme with acknowledgment, we model the transmit buffer as a first-in-first-out (FIFO) queue with bulk service, i.e. bits arrive individually according to a Poisson process, while they leave the queue in groups of up to S bits at a time. The inter-arrival times are exponentially distributed with mean $1/\lambda$ slots where λ is defined as the *input rate* or *traffic*. Upon receipt of an ACK, the set of bits transmitted last are removed from the queue, upon reception of a NACK, the previous (block coded) information bits are retransmitted. We define the time a bit first enters encoding till the time of reception of an ACK (signaling its decoding, correctly or incorrectly) as the service time denoted by Γ and an associated CDF $F_\Gamma(\gamma)$.

It is clear that the distribution of Γ is such that $Pr(\Gamma=kN)=\mathcal{G}(k)$ (where $\mathcal{G}(.)$ is the geometric distribution) and its mean is given by $\bar{\gamma} = \frac{N}{1-P}$ where N is the coding length and P is the probability of receiving a NACK. It is also easy to see that the probability that there are r arrivals in a random service interval is given by

$$k_r = \frac{1}{r!} \int_0^\infty e^{-\lambda\gamma}(\lambda\gamma)^r dF_\Gamma(\gamma).$$

The Z transform of k_r can be related to the Laplace-Stieltjes transform of $F_\Gamma(\gamma)$, $\Omega(.)$ in the following way:

$$K(z) = \sum_{r=0}^{\infty} k_r z^r = \Omega\left(\lambda(1-z)\right), \tag{2}$$

As a first step in calculating the expected delay, we consider the embedded Markov chain describing $\mathbf{q_n}$ the length of the queue at epochs of time just before a service is about to begin. Let $\mathbf{x_n}$ be the distribution of random variable $\mathbf{q_n}$. $\mathbf{x_n}$ satisfies the following recursive equation:

$$\mathbf{x_{n+1}} = \mathbf{x_n Q} \tag{3}$$

where $\mathbf{Q}$ is a matrix whose first S rows are equal to $[k_0 k_1 k_2 \ldots]$ and whose $(S+m)^{th}$, $m = 1, 2, \ldots$ row is equal to $[\overbrace{00\ldots0}^{m} k_0 k_1 k_2 \ldots]$, i.e.

$$\mathbf{Q} = \begin{bmatrix} k_0 & k_1 & k_2 & k_3 & k_4 & . & . & . & . & . \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ k_0 & k_1 & k_2 & k_3 & k_4 & . & . & . & . & . \\ 0 & k_0 & k_1 & k_2 & k_3 & k_4 & . & . & . & . \\ 0 & 0 & k_0 & k_1 & k_2 & k_3 & k_4 & . & . & . \\ 0 & 0 & 0 & k_0 & k_1 & k_2 & k_3 & k_4 & . & . \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix}$$

The embedded Markov chain $\mathbf{q_n}$ is aperiodic, closed and irreducible. Consider the stability:

Condition 1: The encoding-decoding scheme is such that $S > m$, where $m := \lambda\bar{\gamma}$ is the average number of arrivals in a random service time Γ.

Under Condition 1, the chain is positive recurrent, and hence has a unique stationary distribution $\underline{\pi} = (\pi_0, \pi_1, \ldots)$ (also the limit point (steady state)) whose elements satisfy the following equation:

$$\underline{\pi} = \underline{\pi} Q. \tag{4}$$

Taking the Z transform we have

$$\begin{aligned} \Pi(z) &= \sum_{j=0}^{\infty} \pi_j z^j = \sum_{i,j} \pi_i Q_{i,j} z^j & (5) \\ &= z^{-S} K(z)[\Pi(z) + \sum_{j=0}^{S-1} \pi_j (z^S - z^j)] & (6) \end{aligned}$$

where Q_{ij} is the $(i,j)^{\text{th}}$ element of Q. From (5) and (6),

$$\Pi(z) = \frac{\sum_{j=0}^{S-1} \pi_j (z^S - z^j)}{z^S / K(z) - 1}. \tag{7}$$

Since the chain is ergodic, $\Pi(z)$ is finite inside the unit circle. Hence the zeros of the denominator and numerator coincide inside the unit circle. When $m < S$, there are S unique roots inside the unit circle. We also note that $z = 1$ is a trivial root. Define z_i, $i = 1, ..S-1$ as the $S-1$ non unity roots of the denominator, i.e solutions to

$$K(z) = \Omega(\lambda(1-z)) = z^S. \tag{8}$$

Furthermore, the numerator of (7) must be zero at these roots, hence,

$$\sum_{j=0}^{S-1} \pi_j (z_i^S - z_i^j) = 0 \qquad (i = 1, 2..S-1). \tag{9}$$

We also know that $\underline{\pi}$ is a p.d.f, so $\Pi(1) = 1$; equating the limit of (7) at $z = 1$ to 1 we get:

$$\sum_{j=0}^{S-1} (S-j)\pi_j = S - m. \tag{10}$$

Together, (9) and (10) give us S equations to solve for $\pi_0, ..\pi_{S-1}$. Now we are ready to calculate the average queue length at epochs of time just before service takes place (mean of $\mathbf{q_n}$):

$$\bar{q} = \lim_{z\to 1} \frac{\partial \Pi(z)}{\partial z} = \frac{\sum_{j=0}^{S-1} \pi_j (S^2 - j^2) - (S-m)^2 + m}{2(S-m)}. \tag{11}$$

Furthermore, the average waiting time prior to encoding is given by

$$\begin{aligned} \bar{W} &= \frac{1}{m} \int_0^\infty (\bar{q} - m)\nu + \frac{1}{2}\lambda\nu^2) dB(\nu) & (12) \\ &= \frac{\bar{q}}{\lambda} - \frac{m(1-P)}{2\lambda}. & (13) \end{aligned}$$

Therefore, the average delay is given by:

$$\begin{aligned} \bar{D} &= \bar{W} + \bar{\nu} & (14) \\ &= \frac{\bar{q}}{\lambda} - \frac{m(1-P)}{2\lambda} + \frac{N}{1-P} & (15) \end{aligned}$$

Upper and lower bounds on $\bar{q}$ and hence $\bar{D}$ can be obtained by using (10) and the following relation:

$$S(S-j) \le (S+j)(S-j) = S^2 - j^2 \le (2S-1)(S-j). \tag{16}$$

Therefore, from (11), (15) and (16), we can give the lower bound on delay as :

$$L(N, S, \lambda, P_{\text{f}}) = \frac{N}{1-P} + \frac{N(1+SP)}{2(1-P)(S - \frac{\lambda N}{1-P})} \tag{17}$$

and the upper bound as :

$$U(N, S, \lambda, P_{\text{f}}) = \frac{N}{1-P} + \frac{S-1}{2\lambda} + \frac{N(1+SP)}{2(1-P)(S - \frac{\lambda N}{1-P})}. \tag{18}$$

To summarize the analysis,

- The average delay $\bar{D}$ is given by (15) where $\bar{q}$ is given in (11), π_j are got by solving (9) and (10), and z_i are the roots of (8).

- The average delay $\bar{D}$ is upper and lower bounded by functions $U(N, S, \lambda, P_{\mathrm{f}})$ and $L(N, S, \lambda, P_{\mathrm{f}})$ given by (18) and (17) respectively when $\{\mathbf{q_n}\}$ is ergodic.

Before we close this section, we remind the readers that computation of the average delay requires precise computation of the roots of (8) using algorithms developed in [2].

IV. Optimization Problem

In this section, we look at *Objective II*. Given a class of codes $(\mathbb{F}_\beta, \mathbb{D}_\beta)$, we attempt to find the delay optimal encoder-decoder pair $(\mathcal{F}^*, \mathcal{D}^*) \in (\mathbb{F}_\beta, \mathbb{D}_\beta)$. Without loss of generality, $(\mathbb{F}_\beta, \mathbb{D}_\beta)$ define a mapping $P : [\mathbb{N} \times \mathbb{N}] \rightarrow [0, 1]$, where $P(N, S) = \min \{P(\mathcal{F}, \mathcal{D}) : (\mathcal{F}, \mathcal{D})$ are encoder decoder pairs in $(\mathbb{F}_\beta, \mathbb{D}_\beta)$ from $\mathcal{A}^S \rightarrow \mathcal{B}^N\}$ (all other codes are strictly dominated). As a result, our problem reduces to finding (N^*, S^*) which minimizes $\bar{D}(N, S, \lambda, P_{\mathrm{f}})$.

Theorem 1: For a noisy memoryless channel, using the queuing/block coding policy described in Section II, there exists a finite (N^*, S^*) which minimizes the average delay $(\bar{D})$. This gives the optimal block length as well as rate.

Proof: For a fixed N, we know that $P \rightarrow 1$ as $S \rightarrow \infty$. So the set $\{S : S > \frac{\lambda N}{1-P}\}$ is finite. Define:

$$\bar{D}'(N, \lambda, P_{\mathrm{f}}) = \min_{S : S > \frac{\lambda N}{1-P}} \bar{D}(N, S, \lambda, P_{\mathrm{f}}). \tag{19}$$

From (17) and (19) we can conclude that $\bar{D}'(N, \lambda, P_{\mathrm{f}}) \geq N$ and so $\exists N_0, N'$ such that

$$\bar{D}'(N, \lambda, P_{\mathrm{f}}) \geq \bar{D}'(N', \lambda, P_{\mathrm{f}}) \qquad \forall N > N_0 \tag{20}$$

Define N^* and S^* as:

$$N^* = \arg \min_{N \leq N_0} \bar{D}'(N, \lambda, P_{\mathrm{f}}) \tag{21}$$

$$S^* = \arg \min_{S : S > \frac{\lambda N}{1-P}} \bar{D}(N^*, S, \lambda, P_{\mathrm{f}}) \tag{22}$$

It is clear that (N^*, S^*) is finite and minimizes $\bar{D}$. Hence we have proved the existence of an optimal coding scheme (N^*, S^*) which minimizes the average delay $\bar{D}$. ∎

V. Case Study: BSC with Binary Linear Block Codes

In this section, we apply our proposed methodology to a practical scenario with a Binary Symmetric Channel (with the bit crossover probability of P_{b}). We consider the class $(\mathbb{F}_\beta, \mathbb{D}_\beta)$ of encoder-decoders which comprise of Binary Linear Block Codes (BLBC) having two layers of coding, the inner one for error detection and the outer one for error correction[2] for which probability of undetected error $P_{\mathrm{u}} \leq \beta$. For a given BLBC with $N - K$ error correction (EC) bits, the probability of an uncorrected error event, $P_C(N, K)$, is equal to the probability of more than $\lfloor \frac{N-K}{2} \rfloor$ bits being in error. Furthermore, with $K - S$ bits employed for error detection (ED) the probability of an undetected error, P_{u}, is equal to $P_C(N, K) \times 2^{K-S}$ assuming that an erroneous codeword is

[2]This choice of layered coding scheme is known as Type 1 Hybrid ARQ

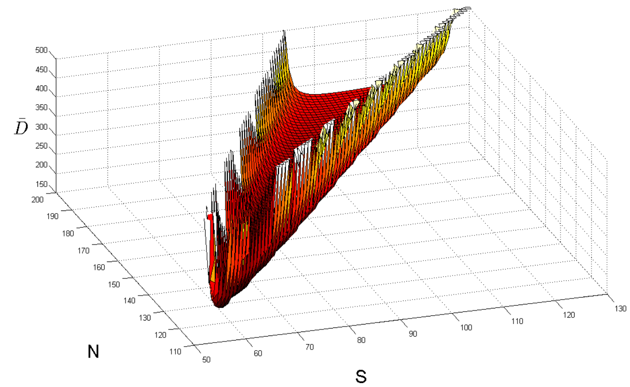

Fig. 2. The average Delay $\bar{D}$ (in slots) for various values of (N, S), $\lambda = 0.47$, $\beta = 10^{-8}$, $P_b = 0.1$

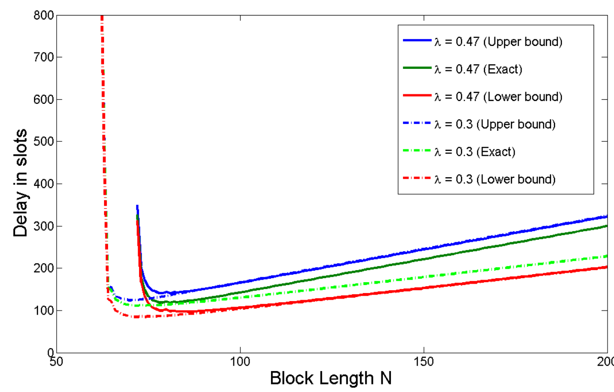

Fig. 3. The optimal delay for various block lengths. ($\beta = 10^{-8}$, $P_b = 0.1$)

uniformly distributed over the set of possible codewords. (sec. 2.3.3 of [13]). This implies that:

$$P(N, S) = P_C(N, K^*)(1 - 2^{-(K-S)}) \tag{23}$$

where

$$P_C(N, K) = 1 - \sum_{i=0}^{\lfloor \frac{N-K}{2} \rfloor} \binom{N}{i} P_b^i (1 - P_b)^{N-i} \tag{24}$$

and

$$K^* = \min\{K : P_C(N, K) \times 2^{-(K-S)} \leq \beta, K \geq S\} \tag{25}$$

So, the encoder-decoder pairs of interest, i.e $(\mathcal{F}, \mathcal{D})$ are identified by the corresponding code length N and ratio $\frac{S}{N}$ and the probability of undetected error P_{u} (23). Given the classification of all encoder-decoder pairs with parameters N,S and $P(N, S)$, we are now interested in a choice of N,S so as to minimize the average bit delay (while meeting $P_{\mathrm{u}} \leq \beta$). To do so, we map each encoder-decoder pair with parameters N,S and $P(N, S)$ to a bulk service queuing problem and use the analysis given in Section III and apply the optimization given in Section IV.

Fig. 2 shows average delay, $\bar{D}$ for feasible values of (N, S),

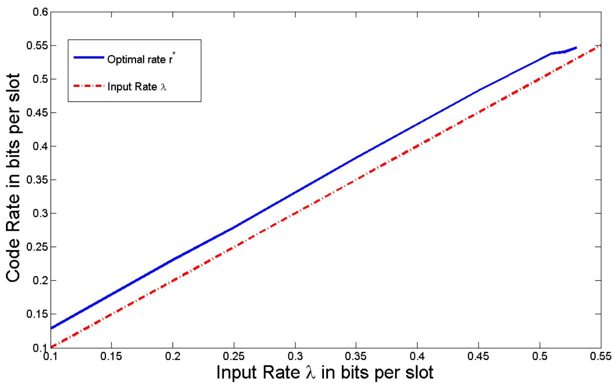

Fig. 4. The optimal output rate as a function of input traffic/rate ($\beta = 10^{-8}$, $P_b = 0.1$)

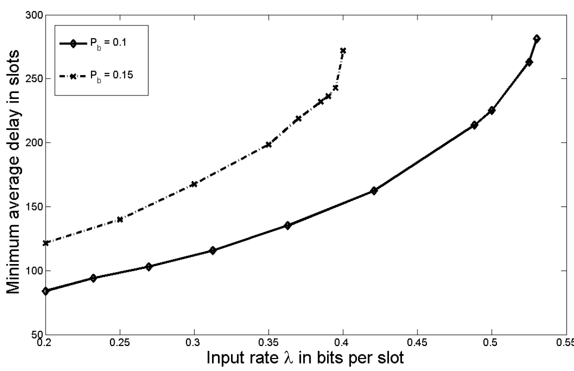

Fig. 5. The plot of minimum achievable delay $\bar{D}^*$ with λ ($P_u = 10^{-8}$)

i.e. those which stabilize the queue. Note that (N, S) may not be feasible under the following three conditions:

1) N is too small, then $P_{\text{u}} > \beta$, $\forall S, K$
2) for a given code length N, if S is too small the bits are not served fast enough
3) for a given N, if S is too large $P(N, S)$ increases and causes too frequent retransmission requests.

Fig. 3 shows the average delay ($\bar{D}$) as a function of N for two values of λ (0.47 and 0.3 bits/slot). In these graphs, S^* is chosen according to (22) to minimize the average delay. In Fig 3, we observe that for rates in the capacity region of the channel, $\bar{D}$ decreases first sharply with N until its optimal value $\bar{D}^*$ at N^*, and then increases monotonically beyond N^*. Furthermore, Fig 3 implies that at small values of λ, sending smaller packets is advantageous since it is effective in reducing waiting time for bits, however too small block lengths will make retransmissions too frequent and hence delay large, negating the effect of smaller N. Fig 3 also demonstrates the sensitivity of delay minimizing block length N^* to the arrival rate: the optimal choice of block length when traffic is estimated to be 0.3 bits/slot creates instability if traffic is increased to 0.47 bits/slot. We will elaborate on this in Sec. IV. Fig. 4 shows the optimal coding rate versus arrival rate λ. We note that the optimal coding rate, $r^* = \frac{S^*}{N^*}$, is always chosen to be larger than λ. However, this gap reduces to zero as λ approaches channel capacity predicting an asymptotic increase in delay as λ nears the capacity of the channel. Fig. 5 confirms this prediction as it plots the optimal delay achievable for different values of λ. As expected, the delay asymptotically grows to ∞ as λ tends to capacity of the channel.

VI. Concluding Remarks

In this paper, we have provided a delay analysis framework for general block coding schemes with retransmission requests (Hybrid ARQ).

In the present paper, the optimal choice of coding rate and length are chosen statically and with perfect knowledge of arrival statistic and channel characterization. In reality such knowledge about traffic and channel is almost never available. As seen in Fig. 3, the static solution exhibits a large sensitivity to the traffic knowledge. Furthermore, adaptive variation of coding rate might substantially improve the performance as it was shown to do in [8] and [11]. The construction of adaptive and robust schemes is an important area of future research.

Further areas of future research include the case of delayed ARQ, the cost of feedback and the impact of ARQ schemes with incremental redundancy.

References

[1] N. T. J. Bailey, "On Queueing Processes with Bulk Service," Journal of the Royal Statistical Society, Series B, 16, pp. 8087, 1954
[2] W.B. Powell, "Stochastic Delays in Transportation Terminals: New Results in the Theory and Application of Bulk Queues," PhD thesis, MIT, 1981.
[3] M.L. Chaudhry and J.G.C. Templeton, "A first Course in Bulk Queues," Wiley Interscience, New York, 1983.
[4] B. P. Dunn and J. N. Laneman, "Rate-Delay Tradeoffs for Communicating a Bursty Source over an Erasure Channel with Feedback," in Proc. Int. Zrich Seminar on Communications, Zrich, Switzerland, Mar. 2008.
[5] A. Ephrimedes and B. Hajek, "Information Theory and Communication Networks: an Unconsummated Union," IEEE Transactions on Information Theory , October 1998.
[6] S. Kittipiyakul, P. Elia, and T. Javidi, "High-SNR Analysis of Outage-Limited Communications with Bursty and Delay-Limited Information," To Appear in IEEE Trans. on Info. Theory.
[7] R. Negi, and S. Goel, "An information-theoretic approach to queuing in wireless channels with large delay bounds," Proc. IEEE Globecom, vol. 1, pp. 116-122, Dallas, USA, Dec. 2004.
[8] I. Bettesh, S. Shamai, "Optimal Power and Rate Control for Minimal Average Delay: The Single-User Case," Information Theory, IEEE Transactions on , vol.52, no.9, pp.4115-4141, Sept. 2006
[9] A. Sahai, "Why block length and delay behave differently for channel coding with feedback," IEEE Transactions on Information Theory, Pages 1860-1886, May 2008
[10] R. Berry and R. Gallager, "Communication Over Fading Channels with Delay Constraints," IEEE Transactions on Information Theory, vol. 48, no. 5, pp. 1135-1149, May 2002.
[11] J. Cao and E.M. Yeh, "Power-Delay Tradeoff Analysis for Communication over Fading Channels with Feedback," proceedings of International Symposium on Information Theory, July 2008.
[12] B. Shrader and A. Ephremides, "A queueing model for random linear coding," Military Communications Conference (MILCOM), October 2007.
[13] D. Bertsekas and R. Gallager, "Data networks," Prentice Hall, Englewood Cliffs, N.J., 2nd ed., 1992.
[14] R. G. Gallager, "Information Theory and Reliable Communication," New York: Wiley, 1968.
[15] T. M. Cover and J. A. Thomas, "Elements of Information Theory," New York: Wiley, 1991.