Communicating Bursty and Delay-sensitive Information over Outage-Limited Channels

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Abstract— **This work analyzes the high-SNR asymptotic error performance when the number of bits that arrive at the transmitter during any time slot is random, the channel experiences outage, and the delivery of bits at the receiver must adhere to a strict delay limitation. It is shown that for a class of arrival processes whose burstiness scales down linearly with $1/\sqrt{\log \mathbf{SNR}}$ the occurrences of channel errors and delay-violation errors can be asymptotically balanced.**

A. Problem Formulation

We are interested in a cross-layer queue-channel optimization problem for bursty and delay-sensitive information sources. Each node is a bursty source of information bits concatenated with an infinite buffer and a constant-rate outage ([1]–[4]) channel to the destination. In particular, we consider the following setting in our study:

- A random number of bits arrive at the transmitter.
- Bits accumulate in an infinite buffer while waiting.
- There is no feedback to the transmitter.
- Communication over the channel is outage-limited.
- The transmitter is unaware of the instantaneous channel state, and hence, operates at a fixed transmission rate, R.
- Coding takes place in T blocks.
- There is a delay bound, D, after which a bit is obsolete.
- A bit is declared in error either when it is decoded incorrectly at the decoder, or violates the delay bound.

Here, the "channel" itself may consist of one or more wireless fading channels; examples include point-point SISO fading [11], [16], a MIMO [12], or a cooperative relay channel [13]–[15]. Note that, in all these cases, for a given transmission rate, R, and a coding block duration, T, there exists a tradeoff between the decoding error versus violation of delay bound.

B. Overview of the Results and Techniques

To gain tractability, we choose to study an asymptotic regime when the signal-to-noise ratio (SNR) is asymptotically high, and hence the "channel" can be beautifully characterized with its *diversity-multiplexing-tradeoff* (DMT) [1]. In our high-SNR asymptotic analysis, we are interested in finding how the asymptotic total probability of error decays with SNR. To keep the problem meaningful, we consider a scenario under which the overall traffic loading of the system is kept fixed, i.e. a case where the arrival rate scales with $\log \mathrm{SNR}$.

From the DMT result, we already know that, if the channel operates below the channel ergodic capacity, the asymptotic probability of channel decoding error decays with SNR. This establishes a best-case scenario for the total error probability. Specifically, we consider a class of i.i.d. arrival processes with light tail (i.e., the processes have all moments finite) whose burstiness (defined as the ratio of the standard deviation over the mean of the number of bits arrived at a timeslot) monotonically goes to zero as SNR goes to infinity. The main result in [16] shows that the optimal decay behavior of the asymptotic total probability of bit error depends on how fast the burstiness of the source scales down with SNR: When the burstiness scales linearly with $\frac{1}{\sqrt{\log \mathrm{SNR}}}$, at the optimal coding duration and transmission rate, the occurrences of channel errors and delay-violation errors are asymptotically balanced, asymptotically optimizing the total error probability.

The significance of the proposed high-SNR analysis is that an asymptotic approximation of the delay violation probability is obtained even when the delay requirement D is finite. The derivation of the asymptotic approximation (Lemma 2 in [16]) is based on a large-deviations analysis and extends the large deviations exponent for a queue with asymptotic number of flows with a deterministic FCFS discipline [10] to one with batch service discipline. Given the validity of the asymptotic probability of bit error for all (finite) D, it is then meaningful to ask about the optimal coding block duration, a question which cannot be answered in studies with asymptotically large or small D (e.g., [5]–[7], [11]–[13]).

The methodology can be applied to several examples of outage-limited communication systems to find the optimal setting of the operating parameters as shown in [14]–[16]. The adaptive extension of the work is an area of future studies.

C. Prior Work

Communication of delay-sensitive bits over wireless channels has been addressed under various assumptions in works such as [5]–[9]. Some, such as [5]–[7], consist of scenarios where the current channel state information (CSI) is assumed at both the transmitter and receiver. while others, [8], [9], focus on scenarios with no CSI at the transmitter but with possibility of retransmission of erroneous bits during an outage. Although our work uses a similar performance measure to [7], it covers the scenarios in which CSI is not available to the transmitter (no CSIT) and there is no retransmission. In such a setting, the variation of the fading channel is combatted via a coding over multiple independent fading realizations.[1] Consequently, our work compliments previous research on the topic by considering the case of no CSIT and no retransmission.

[1] E.g. fading over many coherence time intervals (known as time diversity) [16], or over multiple independent spatial channels, as in MIMO (spatial diversity) [12], or cooperative relay channel (cooperative diversity) [15].

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References

[1] L. Zheng and D. Tse, "Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels," *IEEE Trans. Inform. Theory*, vol. 49, no. 5, pp. 1073–1096, May 2003.

[2] L. Ozarow, S. Shamai (Shitz), and A. Wyner, "Information-theoretic considerations in cellular mobile radio," *IEEE Trans. Veh. Technol.,* vol. 43, pp. 359-378, May 1994.

[3] E. Telatar, "Capacity of multi-antenna gaussian channels," *Europ. Trans. Telecomm.*, vol. 10, no. 6, pp. 585–595, Dec. 1999.

[4] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[5] R. Berry and R. Gallager, "Communication over fading channels with delay constraints," *IEEE Trans. on Information Theory*, vol. 48, pp. 1135–1149, May 2002.

[6] R. Berry, "Optimal power-delay trade-offs in fading channels: small delay asymptotics," *Information Theory and Applications - Inaugural workshop*, San Diego, CA, Feb. 2006.

[7] R. Negi and S. Goel, "An information-theoretic approach to queuing in wireless channels with large delay bounds," *Globecomm'04*, 2004.

[8] I. Bettesh and S. Shamai (Shitz), "Optimal power and rate control for minimal average delay: the single-user case," *IEEE Trans. Inform. Theory*, vol. 52, no. 9, Sept. 2006.

[9] L. Liu, P. Parag, J. Tang, W.-Y. Chen, and J.-F. Chamberland, "Resource allocation and quality of service evaluation for wireless communication systems using fluid models," *IEEE Trans. Inform. Theory*, vol. 53, no. 5, pp. 1767–1777, May 2007.

[10] A. Ganesh, N. O'Connel, and D. Wischik, *Big Queues*, Springer-Verlag, Berlin, 2004.

[11] S. Kittipiyakul and T. Javidi, "Optimal operating point in MIMO channel for delay-sensitive and bursty traffic," *Proc. IEEE Int. Symp. Information Theory (ISIT 2006).*

[12] S. Kittipiyakul and T. Javidi, "Optimal operating point for MIMO multiple access channel with bursty traffic," to appear *IEEE Trans. on Wireless Comm.*.

[13] P. Elia, S. Kittipiyakul, and T. Javidi, "On the Responsiveness-Diversity-Multiplexing Tradeoff," *Proc. of Workshop on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOPT 2007),* Limassol, Apr. 2007.

[14] P. Elia, S. Kittipiyakul, and T. Javidi, "Cooperative diversity in wireless networks with stochastic and bursty traffic," *Proc. IEEE Int. Symp. Information Theory (ISIT 2007).*

[15] S. Kittipiyakul and T. Javidi, "Relay scheduling and cooperative diversity for delay-sensitive and bursty traffic," *Proc. Allerton Conf. Communications, Control and Computing*, Sept. 2007.

[16] S. Kittipiyakul, P. Elia, and T. Javidi, "High-SNR Analysis of Outage-Limited Communications with Bursty and Delay-Limited Information," Submitted for publication, 2007.