Communicating Delay-Sensitive and Bursty Information over Fading Channels

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Outline

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  - Communication of bursty & delay-sensitive data
- Problem Formulation
  - Cross-layer performance at high-SNR
- Examples:
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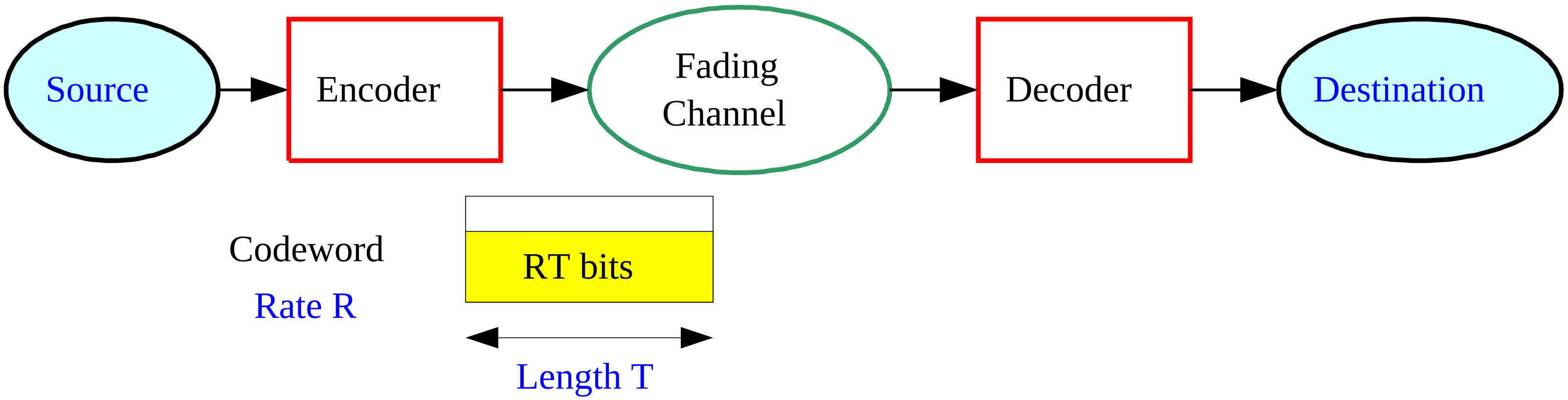
  - Multiple users with scheduling
- Summary and Future Work

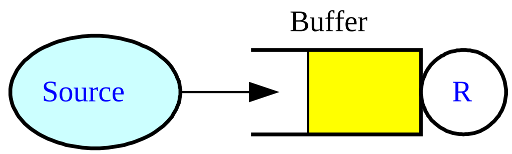
Motivation: Communication over Fading Channel

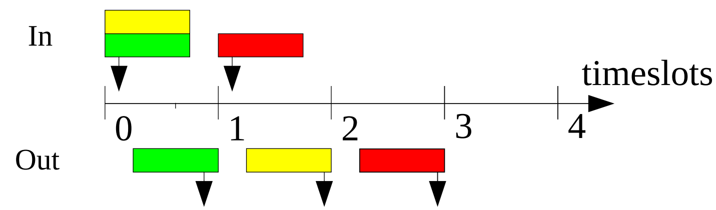


- Block code: length T (symbols), rate R (bits per symbol)
- Avg. signal-to-noise ratio SNR.
- No CSI at transmitter; Perfect CSI at receiver
- If $R <$ "ergodic capacity,"
  - **Decoding Error Probability** P_e decays with T and SNR
  - P_e increasing on R

Communication of Burtsy & Delay-Sensitive Data

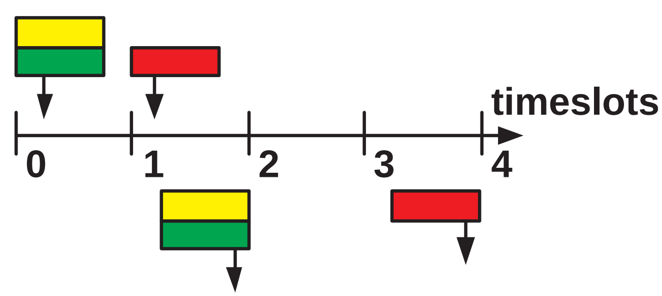
- Introduce a buffer





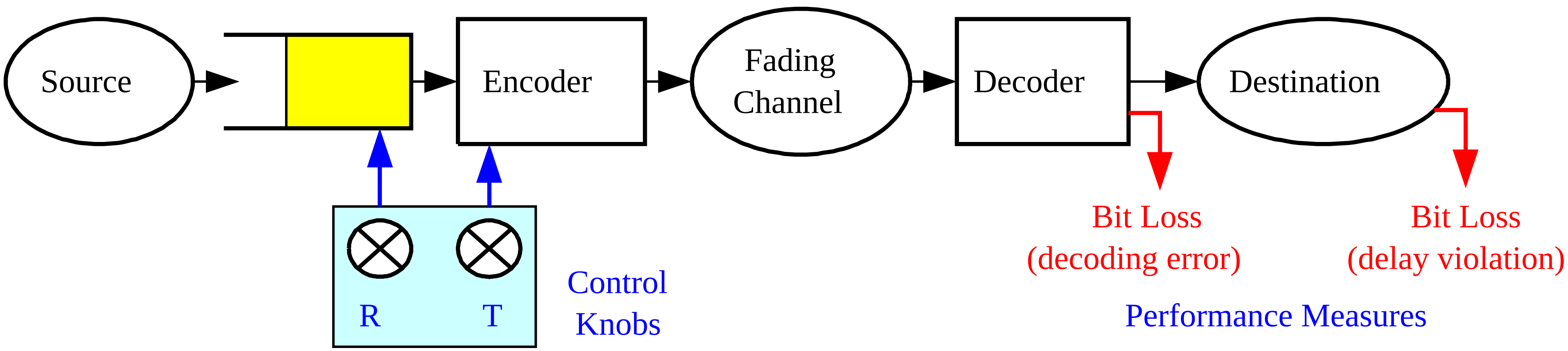
  - Bits arrive at each timeslot. Serve R bits every timeslot
  - Delay $=$ departure time - arrival time
  - Delay requirement D
  - **Probability of Delay Violation** $P_{\text{dv}} := P(\text{steady-state delay} > D)$

- Introduce "Service Failure": failure probability P_{e}. No retransmission.
- Introduce **Batch Service** or "Bus Service"
  - Serve RT bits every T timeslots.
  - Less failures, but more delay
  - $P_{\text{dv}}(R, T)$ depends on $R(\downarrow)$ and $T(\uparrow)$



Formulation: Communication of Bursty & Delay-Sensitive Data over Fading Channel

- Complete picture:



- Overall performance degradation is due to
  - Decoding error over the fading channel
  - Violating the delay bound D

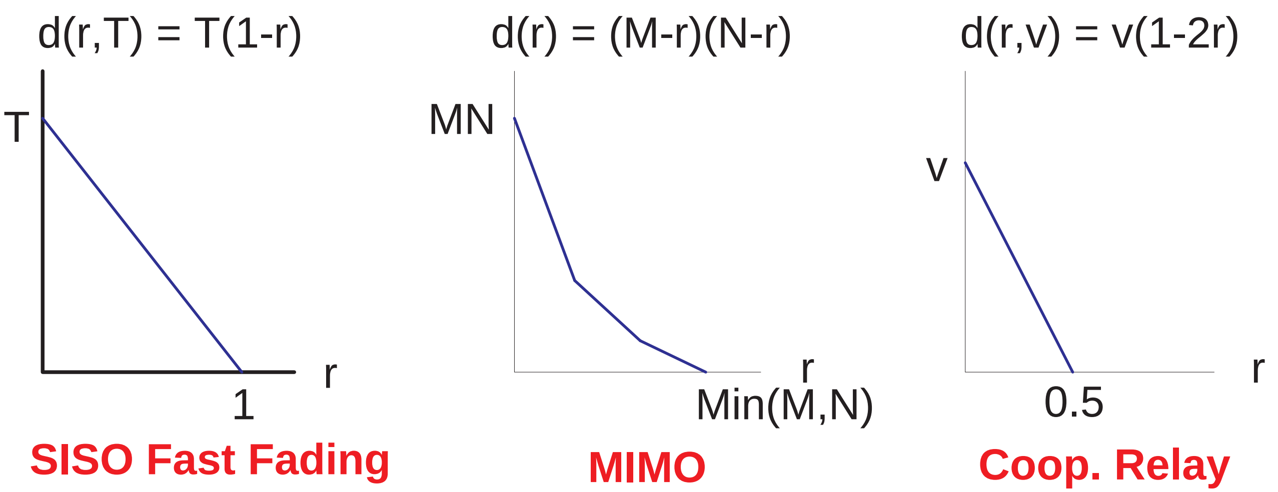
Objective: Choose optimal R^* and T^*, minimizing the **total error probability**

$$P_{\mathsf{tot}}(R,T) = P_{\mathsf{e}}(R,T) + (1 - P_{\mathsf{e}}(R,T))\, P_{\mathsf{dv}}(R,T)$$

Review: High-SNR approximation of P_e

Diversity-Multiplexing-Tradeoff [Zheng-Tse '03]

- Consider a family of codes, one at each SNR.
  - Code Rate $R = r \log \mathsf{SNR}$
  - Error probability $P_e^{\mathsf{SNR}}(r) \doteq \mathsf{SNR}^{-d(r)}$
- **Multiplexing** gain: r
- **Diversity** gain: $d(r) = -\lim_{\mathsf{SNR}\to\infty} \frac{\log P_e^{\mathsf{SNR}}}{\log \mathsf{SNR}}$



Result: High-SNR Asymptotic for the Overall System

- Consider high-SNR asymptotic regime
- Find source conditions where

$$P_{\text{dv}} \doteq \text{SNR}^{-I(r,T)}$$

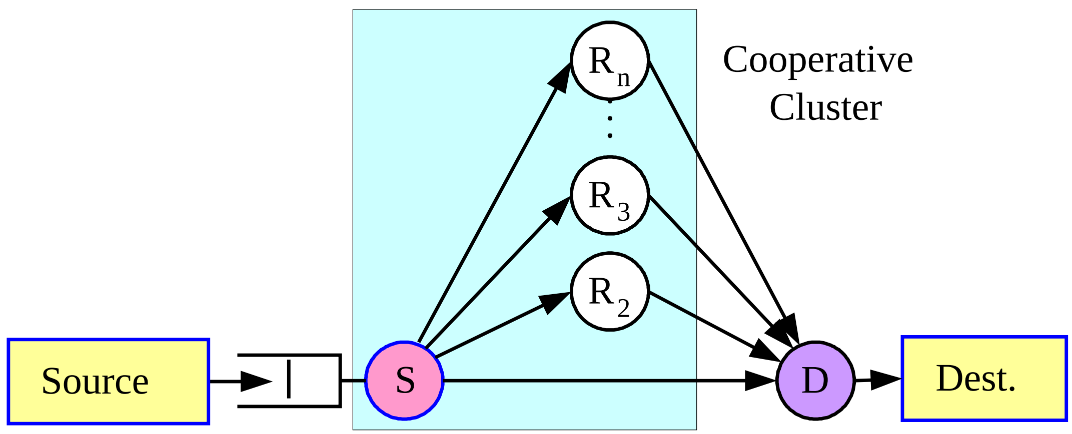
and total probability of error asymptotically decays with SNR

$$\begin{aligned} P_{\text{tot}} &\doteq P_{\text{e}} + P_{\text{dv}} \\ &\doteq \text{SNR}^{-d(r,T)} + \text{SNR}^{-I(r,T)} \\ &\doteq \text{SNR}^{-\min\{d(r,T), I(r,T)\}} \end{aligned}$$

- Find optimal r^* and T^* maximizing the decay exponent of P_{tot}
- A practical source with desired P_{dv}:
  - **Many-flows source** $A_t^{\text{SNR}} = A_t^1 + \cdots + A_t^{\log \text{SNR}}$
  - Number of flows scales with $\log \text{SNR}$

Applications: Optimal Operating Points

- Single source
  - SISO fast-fading channel
  - MIMO slow-fading channel
  - Cooperative relay channel



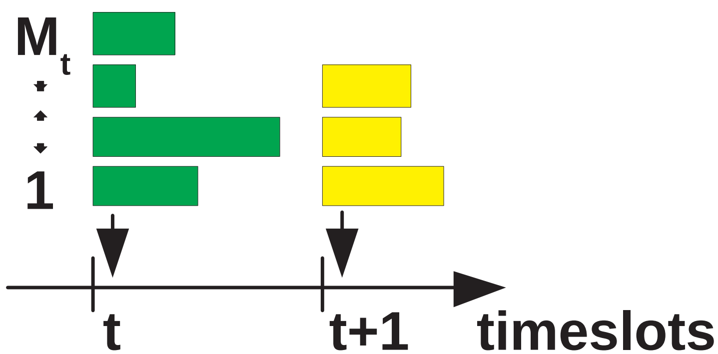
- Multiple sources: MIMO Multiple Acccess

Example: CPE over SISO with Rayleigh Fast-Fading

- CPE source: Compound Poisson arrivals with Exponential packet size:

$$A_t^{\mathsf{SNR}} = \sum_{i=1}^{M_t} Y_{i,t}$$

  - Poisson number of packets: M_t with rate $\nu \log \mathsf{SNR}$
  - Exponential packet size: $Y_{i,t}$ with mean $1/\mu$



- This source is many-flows scaling

Example: CPE over SISO with Rayleigh Fast-Fading

- Probability of delay violation:

$$P_{\mathsf{dv}}(r,T) \doteq \mathsf{SNR}^{-I(r,T)}$$

where

$$I(r,T) = \min_{\substack{t\in\mathcal{Z}^+:\\ tT+T-1-k>0}} (tT+T-1-k)\Lambda^*\left(r+\frac{(D+1-2T)r}{tT+T-1-k}\right)$$
$$\approx \mu(r-\lambda)(D+1-2T)$$

- Bits are transmitted over SISO channel with Rayleigh fast fading
  - Recall $\quad P_{\mathsf{e}}(r,T) \doteq \mathsf{SNR}^{-T(1-r)}, \;\; 0 \le r \le 1$

- Optimal coding duration T^* and multiplexing rate r^* balances exponent of P_{e} and P_{dv}:

$$T(1-r) = \mu(r-\lambda)(D+1-2T)$$

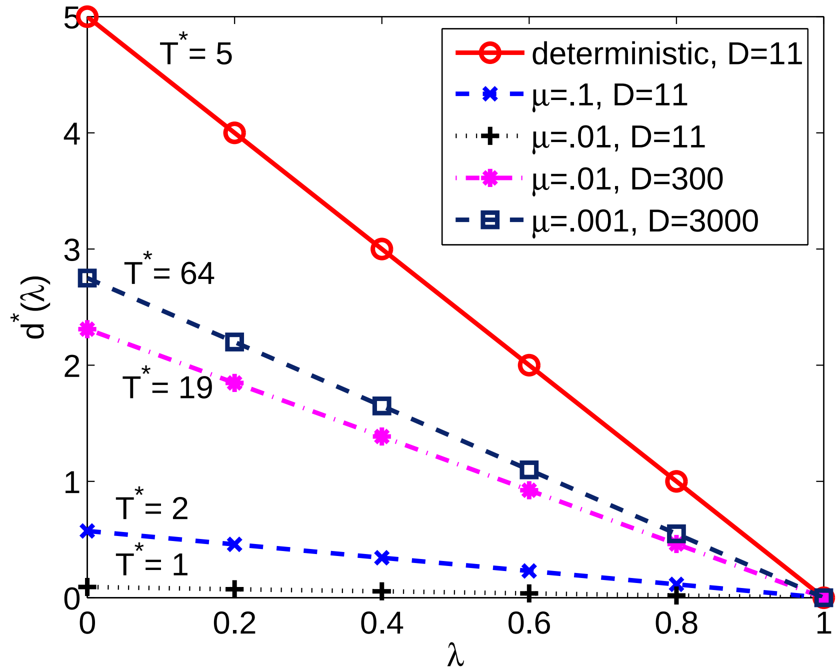
while maximizing the rate of decay.

Example: CPE over SISO with Rayleigh Fast-Fading

- Optimal block length T^* and code rate r^*:

$$T^* \approx \frac{1}{1+\frac{1}{\sqrt{2\mu}}} \frac{D+1}{2} \qquad\qquad r^* \approx \lambda + \frac{1-\lambda}{1+\sqrt{2\mu}}$$

- Optimal negative SNR exponent ($P_{\text{tot}} \doteq \text{SNR}^{-d^*}$) vs. arrival rate



Multiple Sources

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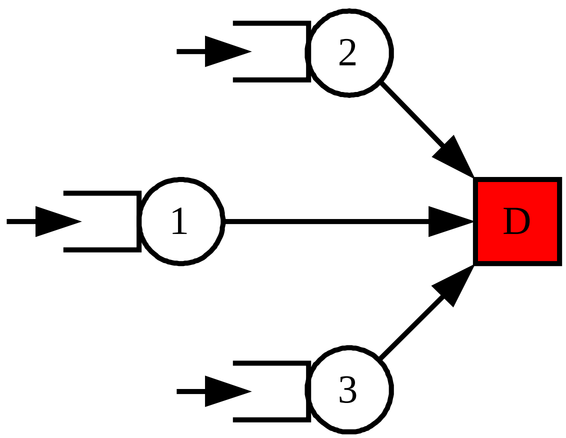
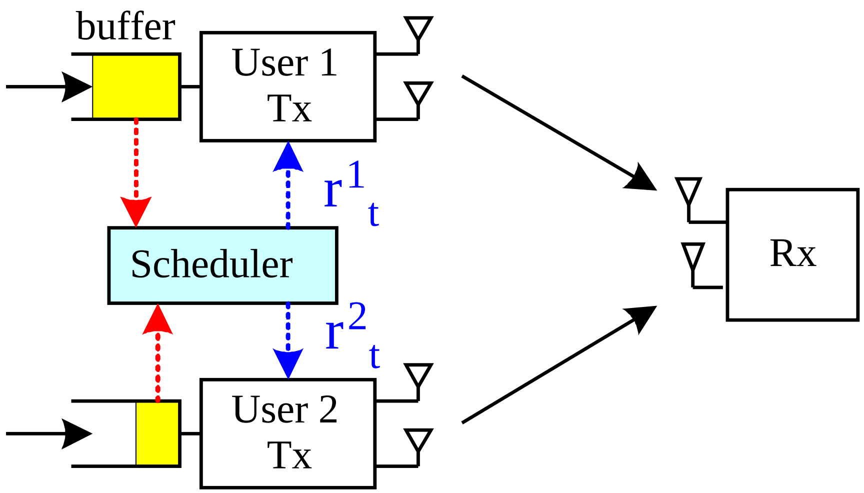


- Time-sharing (TDMA) or Multiple Access
- Fixed or dynamic scheduling

MIMO Multiple Access with Max-Weight Scheduling

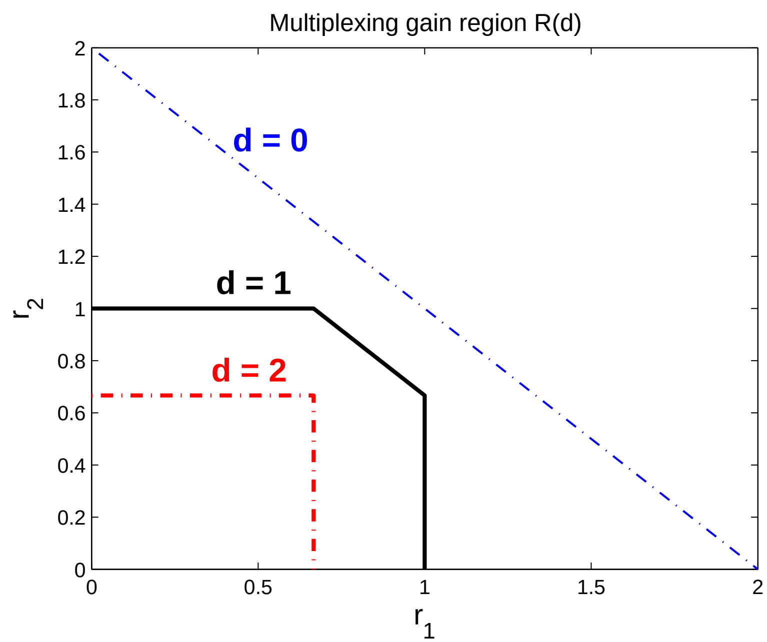


- Operating at channel diversity d, assign multiplexing gains

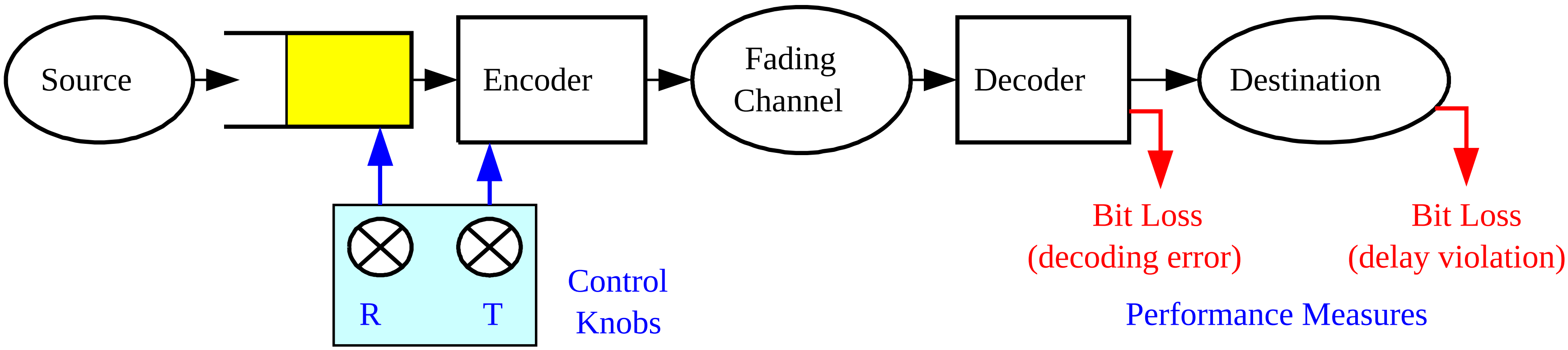
$$\mathbf{r}_t = (r_t^1, r_t^2) \in \mathcal{R}(d)$$

maximizing $< \mathbf{Q}_t, \mathbf{r}_t >$

- Focus on "buffer overflow" probability



Summary and Future Works



Possible extensions:

- Closed-loop control
  - Feedbacks (ACK/NACK) to encoder/source
  - Dynamic adjustment: adaptive to queue, source, channel
- Multi-hop networks
- More general arrival processes e.g. Internet traffic
- Sensitivity analysis to arrival statistics
- Validity at medium SNR