Throughput Maximization and IR-HARQ Optimization for URLLC Traffic in 5G System

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Supporting New Applications:




Mission-critical control

smart grid (5ms for tx/grid backbone, 50ms for grid backhaul)

Industrial Automation

real time control (20µs – 10 ms), time-critical sensing (10ms), over-the-air: 0.25~1 ms

HF Trading & eCommerce

1ms delay advantage = 100M$/year

A page load slowdown of 1 sec could cost 1.6B$ in sales each year (Amazon)

Media & Entertainment

4K Video, live streaming in crowded areas (20ms), collaborative gaming (20ms)

AR/VR

MTP 15~20 ms // over-the-air:1~5 ms

Tactile Internet

1ms e2e latency

Automotive industry

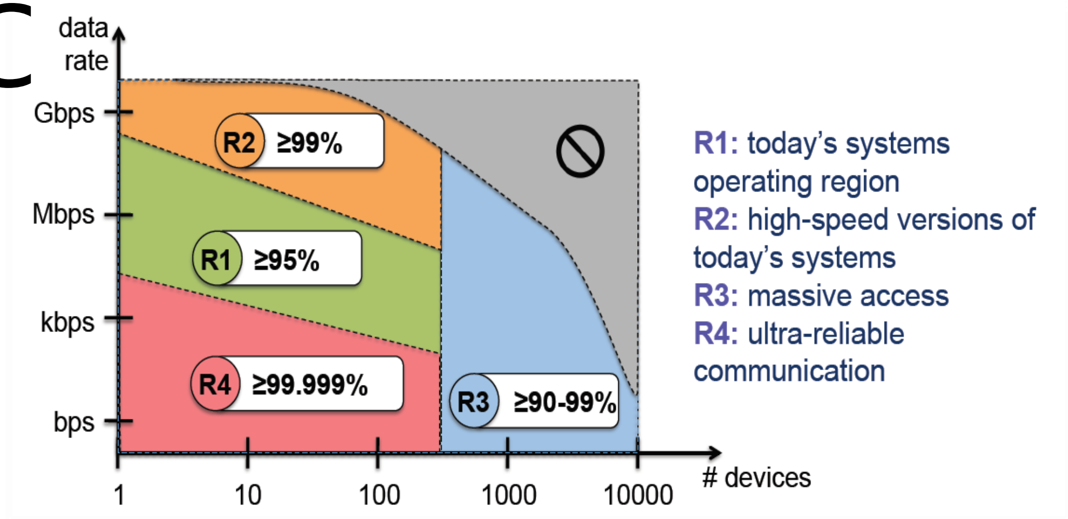
autonomous/cooperative driving, V2X (3-10ms), V2N for remote vehicle operation (10-30ms E2E)

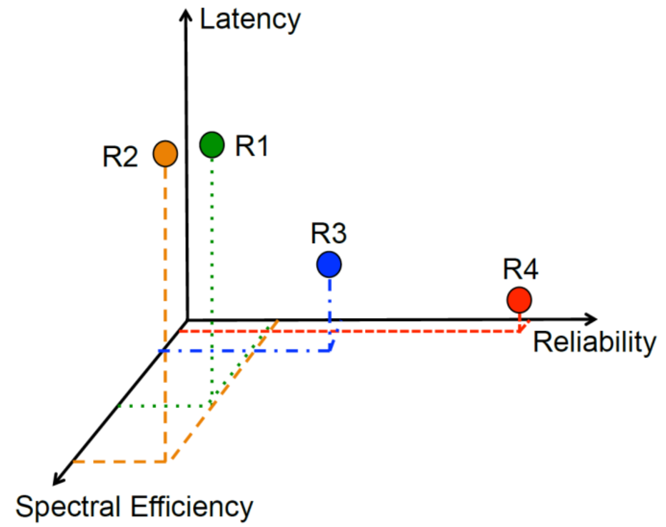
Healthcare

video/AR for remote surgery (100ms), real-time command/control (10-100ms)



New Operation Regimes - URLLC

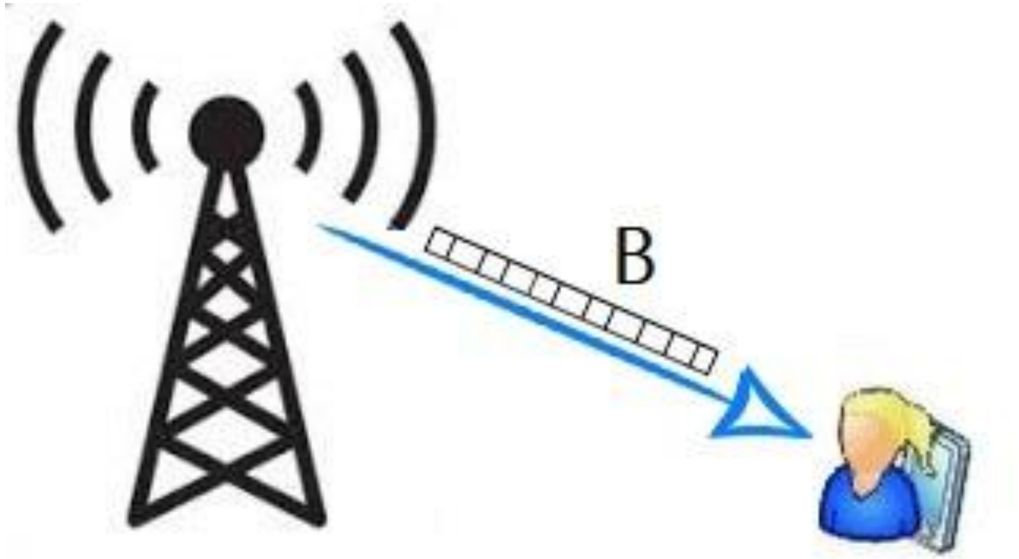




From F. Boccardi et al. "Five Disruptive Technology Directions for 5G

Use case	Latency (ms)	Reliability (PEP)	Data size (bytes)	Communication range (m)
Industrial automation	0.25 – 10	$10^{-6} - 10^{-9}$	10 – 300	10 – 100
Smart grids	5 – 50	10^{-6}	80 – 1000	Few m to km
Intelligent transport systems	5 – 100	$10^{-3} - 10^{-5}$	500 – 1k	200 – 5000
Telemedicine	1 – 10 (haptics) 20 – 100 (video, audio)	10^{-5}	200 – 4k	< 200 km

System model



- Point to Point communication
- Fixed number “B” of information Bits
- Messaged transmitted using “N” channel uses and “P” power
- Within time coherence interval

Error Probability: $\mathcal{E}$

- If block-length $N \to \infty$ and mutual information above a threshold then:
  $\varepsilon \to 0$

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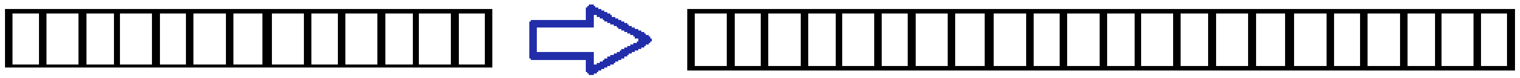
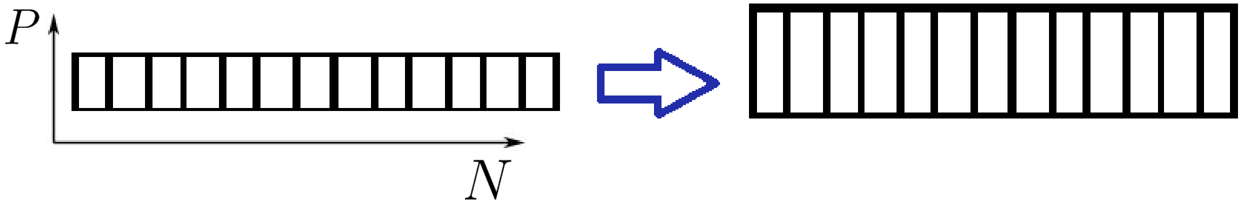
  
  - Increase P :
  

Error Probability: $\mathcal{E}$

$$\varepsilon \approx Q\left(\frac{N\ln(1+P) - B\ln 2 + \frac{\ln N}{2}}{\sqrt{N(1-\frac{1}{(1+P)^2})}}\right)$$

[1] Y. Polyanskiy, “Channel coding: Non-asymptotic fundamental limits”, Ph.D. dissertation, Princeton University, Nov. 2010.

[2] M. Hayashi, “Information spectrum approach to second-order coding rate in channel coding,” IEEE Trans. on Inf. Theory, vol. 55, no. 11, pp. 4947–4966, Nov. 2009

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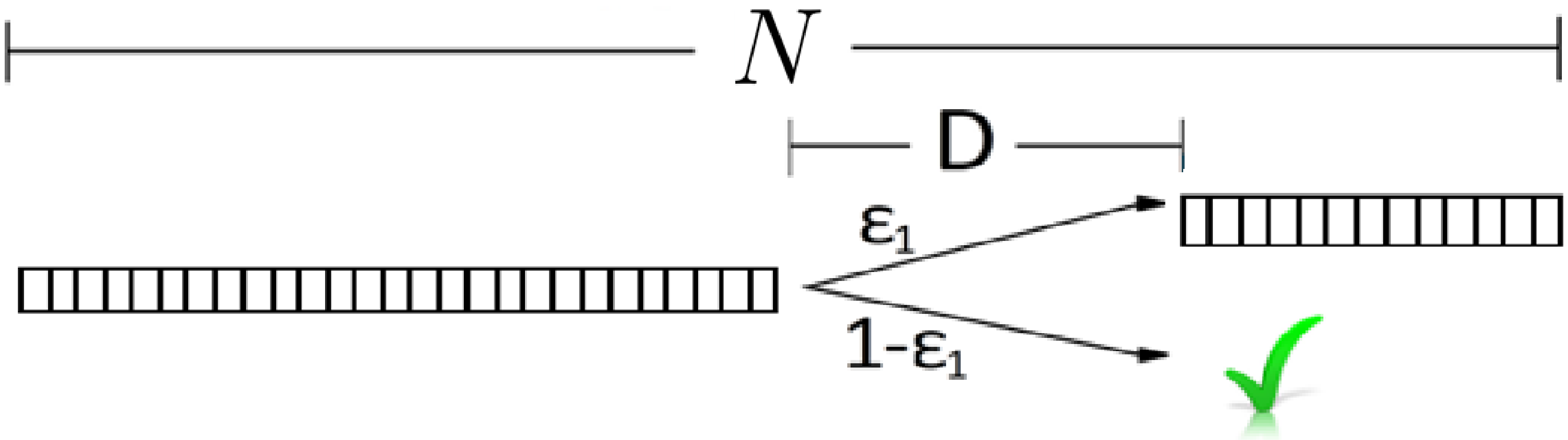
- Incremental Redundancy Hybrid Automatic Repeat Request (IR-HARQ). For $M = 2$ rounds:



Error Probability ε_m for IR-HARQ at m round

$$\varepsilon_m \approx Q\left(\frac{\sum_{i=1}^{m} n_i \ln(1+P_i) - B\ln 2}{\sqrt{\sum_{i=1}^{m} \frac{n_i P_i (P_i+2)}{(P_i+1)^2}}}\right)$$

Optimization Problem, URLLC,
Fixing: B information bits, M IR-HARQ rounds, $D = 0$

$$s.t. \quad \varepsilon_M \leq \varepsilon_{\text{rel}} \qquad\qquad (R)$$

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$$

Optimization Problem, URLLC,
Fixing: B information bits, M IR-HARQ rounds, $D = 0$

$$\min_{n_1, P_1, \ldots n_M, P_M} \quad \frac{B(1-\varepsilon_M)}{\sum_{m=1}^{M} n_m \varepsilon_{m-1}}$$

$$s.t. \quad \varepsilon_M \leq \varepsilon_{\text{rel}} \qquad (R)$$

$$\sum_{m=1}^{M} n_m \leq \mathrm{N_l} \qquad (L)$$

$$\sum_{m=1}^{M} n_m P_m \varepsilon_{m-1} \leq \mathrm{E}_b \qquad (E)$$

Towards a Solution:

$$\max_{n_1,P_1,\ldots n_M,P_M} \quad \sum_{m=1}^{M} n_m \varepsilon_{m-1}$$

$$s.t. \quad \varepsilon_M = \varepsilon_{\text{rel}} \qquad (R)$$

$$\sum_{m=1}^{M} n_m \leq \mathrm{N_l} \qquad (L)$$

$$\sum_{m=1}^{M} n_m P_m \varepsilon_{m-1} = \mathrm{E}_b \qquad (E)$$

- Nominator almost constant as B is fixed and $\varepsilon_{rel} \leq 10^{-5}$.
- Achieving lower than required error pr. leads only to waste of resources.
- Increasing the energy improves latency and throughput.

Let state: $S_m = (\varepsilon_m, \sum_{i=1}^{m} n_i, \sum_{i=1}^{m} n_i P_i \varepsilon_{i-1})$

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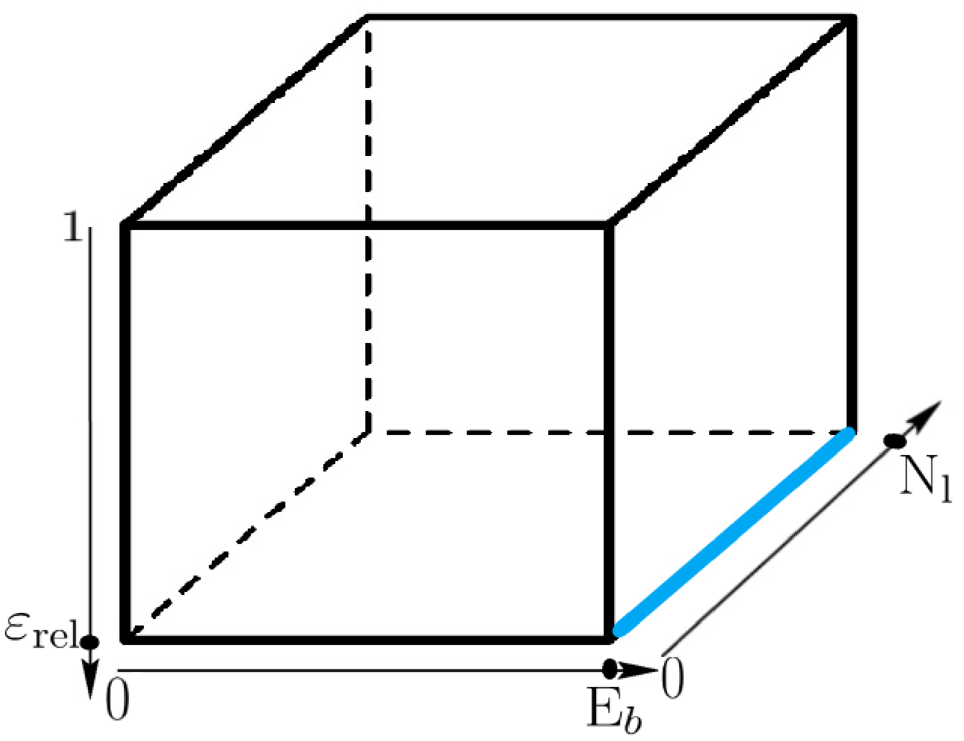
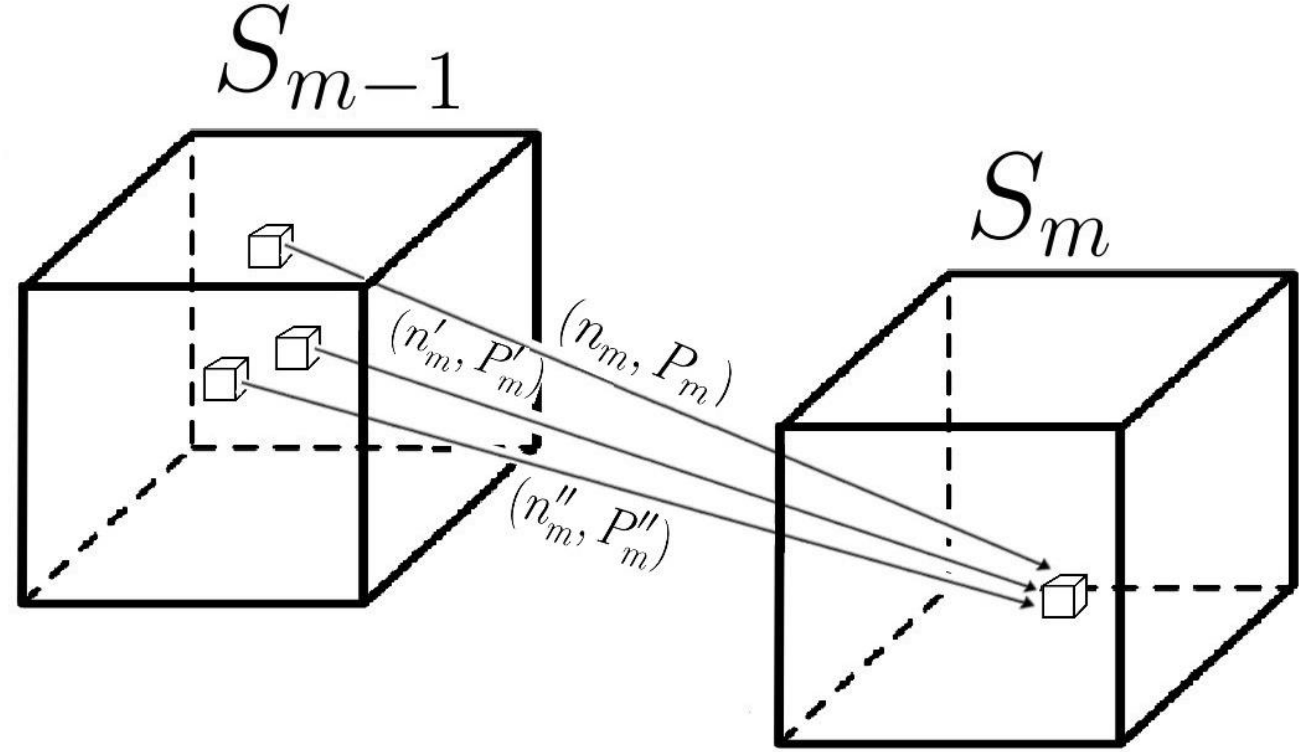


- Every state $m < M$ belongs inside the cube.
- The last state S_M lies in the blue line

Dynamic Programming

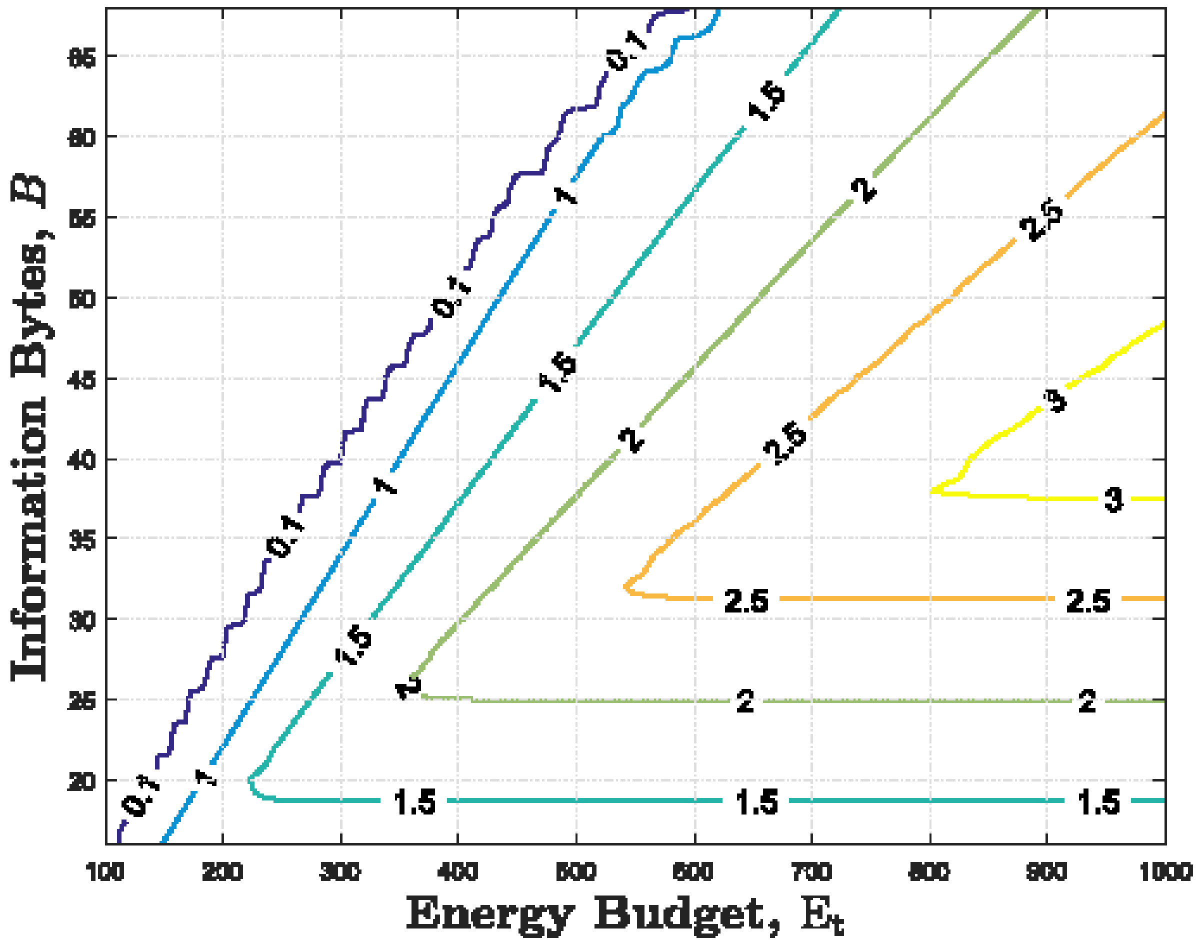


- To be optimal in S_m necessarily S_{m-1} has to be reached optimally.

Remarks:

- If the problem is solved for $(M, \varepsilon_{\mathrm{rel}}, \mathrm{N_l}, \mathrm{E}_b)$ then any other parameter combination with $(M' \leq M, \varepsilon'_{\mathrm{rel}} \geq \varepsilon_{\mathrm{rel}}, \mathrm{N_l}' \leq \mathrm{N_l}', \mathrm{E}'_b \leq \mathrm{E}_b)$ is solved also, assuming that every “cube” containing the states was stored.
- Unfortunately this doesn’t hold with B and the dynamic programming solution has to be computed again.
- This method was applied in a previous publication for energy minimization in [*3]A. Avranas, M. Kountouris, and P. Ciblat, “Energy-latency tradeoff in ultra-reliable low-latency communication with retransmissions,” IEEE J. Sel. Areas Commun., Oct. 2018.*

Throughput vs. energy and information bits for $M = 3$, $\varepsilon_{\mathrm{rel}} = 10^{-5}$ and $\mathrm{N_l} = 600$



Thank you

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