No Symbol Left Behind

a Link-Layer Protocol for Rateless Codes

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Preview of Key Ideas
1. Transmission Schedules & Rateless Codes
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2. Backward Induction
Preview of Key Ideas

1. Transmission Schedules & Rateless Codes

2. Backward Induction

3. The Decoding CDF
Automatic Repeat Request (ARQ)
Hybrid ARQ (HARQ)
Type II HARQ

Start → payload → error? → redundancy → error?

ACK → NAK → NAK
Type II HARQ
Type II HARQ

Start

payload

error?

redundancy

error?

NAK

ACK

NAK
Type II HARQ

Start → payload → error? → redundancy → error? → NAK → ACK
Type II HARQ

- Start
- Payload
- Error?
- Redundancy
- NAK
- Error?
- NAK
- ACK

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Type II HARQ

Start

payload

error?

NAK

redundancy

error?

NAK

ACK
Transmission Schedule

Feedback interval: 0 1
Transmission Schedule

Feedback interval: 0 1 (5, 5)
Rateless Codes

- Prefix property (variable-length decoder)
- Code is stronger when prefix is longer
- Characterized by decoding CDF
- (Potentially) also:
  - unlimited length
  - no need to pick constellation
  - tolerates arbitrary erasures
Rateless Codes

Aggressive

Feedback interval: 0 1 2 3 4 ...

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Rateless Codes

Aggressive
Feedback interval:

Moderate
Feedback interval:

Conservative
Feedback interval:

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Backward Induction

# symbols sent so far:

Legend

- Strategy known
- Strategy still unknown
Backward Induction

Legend

- **Strategy known**
- **Strategy still unknown**

# symbols sent so far:

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 ...
Backward Induction

Legend

- **Strategy known**
- **Strategy still unknown**

# symbols sent so far:

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 ...
Backward Induction

Legend

- **Strategy known**
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Backward Induction

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Backward Induction

Legend

- Strategy known
- Strategy still unknown

# symbols sent so far:
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 ...

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Backward Induction

Legend

- **Strategy known**
- **Strategy still unknown**
- **Strategy to be found**

# symbols sent so far:

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 ...
Backward Induction

Legend
- Blue: Strategy known
- Yellow: Immediate cost to send so many symbols
- Grey: Strategy still unknown
- Light grey: Strategy to be found

# symbols sent so far:

0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | ...

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Backward Induction

Legend

- **Strategy known**
- **Strategy still unknown**
- **Strategy to be found**
- **Immediate cost to send so many symbols**
- **Cost of best fall-back plan (in event of NAK)**

# symbols sent so far:

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>...</th>
</tr>
</thead>
</table>

Strategy to be found

Immediate cost to send so many symbols

Cost of best fall-back plan (in event of NAK)
Backward Induction

# symbols sent so far:

- **Strategy known**
- **Strategy still unknown**
- **Strategy to be found**

|   | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | ...
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

Legend:
- **Blue** Strategy known
- **Gray** Strategy still unknown
- **Gray** Strategy to be found
- **Yellow** Immediate cost to send so many symbols
- **Brown** Expected cost of fall-back

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Backward Induction

Legend
- **Blue**: Strategy known
- **Light Grey**: Strategy still unknown
- **Orange**: Strategy to be found
- **Yellow**: Immediate cost to send so many symbols
- **Brown**: Expected cost of fall-back

# symbols sent so far:

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | ...

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Induction: Base Case

• Need to know strategy for all $m > n$ to find strategy for $n$.

• How to bootstrap this infinite recursion?

• Solution: modify the inputs to ensure that a steady-state strategy exists

• Full details in the paper
Summary of Results

- Tested with Strider, spinal, raptor codes
- Overhead ↓ 2.6–5.4x versus ARQ, HARQ
- Throughput ↑ 26%
- Throughput when inputs are only estimated is just 1.57% less vs. fully known inputs
- Estimation converges within 10-20 packets
Decoding CDFs

P(decoded)

# of symbols
Decoding CDFs

P(decoded)

1

# of symbols

0

High SNR

Low SNR
Decoding CDFs
(empirical for spinal codes)
Decoding CDFs
(empirical for spinal codes)
Decoding CDFs
(empirical for raptor codes)
Key Ideas in RateMore

- Even rateless codes need rate adaptation
- More feedback = fewer wasted symbols
- Induction picks # of symbols per feedback
- Decoding CDF captures code and channel
- Coordination helps amortize cost (paper)
Fading channel estimation