On Forward Error Correction

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5G Requirements

A Bird’s-Eye View

Relative to the contemporary cellular deployments:

- **Uniform QoE data rate:** 10x, 100Mbps
- **Peak data rates (low mobility/hot-spots):** 20x, 10-20Gbps
- **End-to-end latency:** < 5ms
- **Over-the-air latency:** < 1ms
- **Spectral efficiency:** 3x
- **Data traffic with same energy:** 100x
- **Mobility:** 500km/h
- **Number of simultaneous connections:** 10x, 10^6/km^2
- **Cellular IoT:** power/cost efficiency, larger indoor coverage and reduced complexity

Area and Energy Efficiency Targets

- **Area efficiency** (estimates) to achieve 20Gbps data rate:
  - 2Gbps/mm^2 at the UE
  - 10mm^2 is typical assumption in 3GPP LTE Turbo code implementation efforts
- **Energy efficiency** to “fit on a smartphone”:
  - 50pJ/information bit (assumes 1W available for decoding)

Impact of the 5G Use Cases on Coding

- **enhanced Mobile Broadband (eMBB)**
  - UHD video streaming, information showers/hotspots
  - high throughput
  - medium-long packet lengths
  - low latency (<5ms: end-to-end, <1ms: over-the-air)
  - wide range of operating points, wide range of modulation & coding support

- **ultra Reliable Low-Latency (uRLL)**
  - remote access/robotics, virtual reality, cloud computing, vehicular communication
  - small-medium throughput
  - lower code rate operation
  - extremely low error floors
  - almost-wireline latency, low encoding/decoding latency (small-medium packet lengths)

- **massive Machine Type Communication (mMTC)**
  - smart home, office, store, wearable technology
  - small throughput
  - long-term stand-alone operation after deployment, low energy budget i.e. high energy efficiency
  - low device cost for large scale deployment i.e. high area efficiency via simple implementations
  - good error performance at low throughputs (machines deployed in extremely poor channel conditions)
  - short packet lengths
State of Standardization – 3GPP RAN1

Current agreement:

**Flexible LDPC** as the single channel coding scheme for:
- UL eMBB data channels: large block sizes ($k > 1024b$)
- UL eMBB data channels: small block sizes ($128b \leq k \leq 1024b$)
- DL eMBB data channels: all block sizes

**Polar Coding**
- UL control information for eMBB
- DL control information for eMBB

Future Discussion:

- uRLL and mMTC: LDPC/Polar/Convolutional/Turbo

* To be confirmed unless significant issues are identified by the RAN1 Jan adhoc in relation to performance, latency, power consumption and implementation complexity.
** Except FFS for very small block lengths ($k < 128b$) where repetition/block coding may be preferred

Ref: Final Report of 3GPP TSG RAN WG1 #86 v1.0.0, Gothenburg, Sweden, 22nd – 26th August 2016
On Considerations for FEC Selection

Part-1

• **Implementation complexity vs theoretical complexity**
  - Efficiency: Area \((Gbps/mm^2)\) and Energy \((pJ/b)\) must be based on actual implementations, not theoretical analysis.
  - Computational complexity is inadequate. structured vs random LDPC have similar computational complexity significantly different implementation complexity.

• **Flexible Implementations**
  - tradeoff: complexity and flexibility
  - complexity of the entire coding chain: e.g. code block segmentation, rate matching, HARQ, soft buffer etc. is affected
  - RC designs imply a single coding chain:
    • hardware reuse for various block lengths/rates
    • crucial for efficient HARQ implementations
  - switching-based designs imply multiple coding chains:
    • multi-mode decoders cannot reuse hardware, hence area-inefficient
    • a benefit: optimized design for a subset of block lengths/rates
On Considerations for FEC Selection

Part-2

• **Latency oriented implementation complexity and performance** (concern for uRLL & control channels)
  
  - latency of both types to be accounted for: processing (implementation) & structural (code design)
  
  - e.g. latency analysis based on implementation can be used to optimize decoding parameters such as number of iterations for iterative decoding.

• **Standard/IP Experience and Future-proofing**
  
  - Commercially proven designs and architectures. For example:
    
    • Turbo: *3GPP LTE, WCDMA, DVB*
    
    • LDPC: *IEEE 802.11n, IEEE 802.16, DVB*

  - Codes with tried and tested implementations hold the promise of future modification for the large umbrella of 5G requirements.
On Considerations for FEC Selection
Part-3

HARQ Challenges

- **Channel**
  - Fading & path blockages
  - Code design must exploit diversity in time and space

- **Frame Structure & TTI**
  - Flexible UL/DL switch periodicity
  - Fast reporting of ACK/NAK

- **Device Capability**
  - LLR buffer capacity
  - Decoding error performance at given complexity

- **Rate Compatibility and Support**
  - Implementation complexity vs flexibility tradeoff

- **uRLL**
  - Any saving in latency is significant

- **mMTC**
  - Small packet HARQ process
  - Decoding: low complexity to begin with
  - High reliability for inopportune placement (e.g. machine situated underground)
HARQ Latency Reduction
Coding for Diversity

Need for HARQ
• fragile channels
  • cell edge delivery
  • dependence on directional links
  • path blockages (small cells, dense urban): beam repair is time expensive esp. for uRLL
• unknown channels
  • estimation based on small-scale parameters can be prohibitively expensive at these bandwidths esp. for mMTC

Proposed Direction
• Exploit diversity owing to
  • coherence time reduction
    • migration to higher frequencies
    • environment object density
  • trading bandwidth for latency/reliability
    • transmission over different bands (licensed and unlicensed)
  • antenna count
    • spatially diverse beams to combat path blockages

Fig. Downlink communication between a BS-UE pair in a dense urban environment. Dashed lines are non-specular paths, one of the paths is blocked by a vehicle.
HARQ Latency Reduction
Coding for Diversity

• Techniques to minimize/eliminate feedback to improve latency
  • multiple RVs available at the receiver at the same time
  • perform pre-decoding tests on RVs
  • for reliability-critical use cases such as uRLLC, (Chase/IR) combine best RVs to maximize gain
  • for energy-critical use cases such as mMTC, select best RV to effectively operate at high code rate to maximize energy saving

• Improving efficiency of HARQ based on rateless codes by utilizing coding and diversity gains