On Forward Error Correction

Swapnil Mhaske, Predrag Spasojevic
WINLAB, Rutgers University, NJ, USA

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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)

Samsung 5G Vision, 2015: http://www.samsung.com/global/business-images/insights/2015/Samsung-5G-Vision-0.pdf

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
- **Rate Compatibility and Support**
  - Implementation complexity vs flexibility tradeoff
- **Frame Structure & TTI**
  - Flexible UL/DL switch periodicity
  - Fast reporting of ACK/NAK
- **Device Capability**
  - LLR buffer capacity
  - Decoding error performance at given complexity
- **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

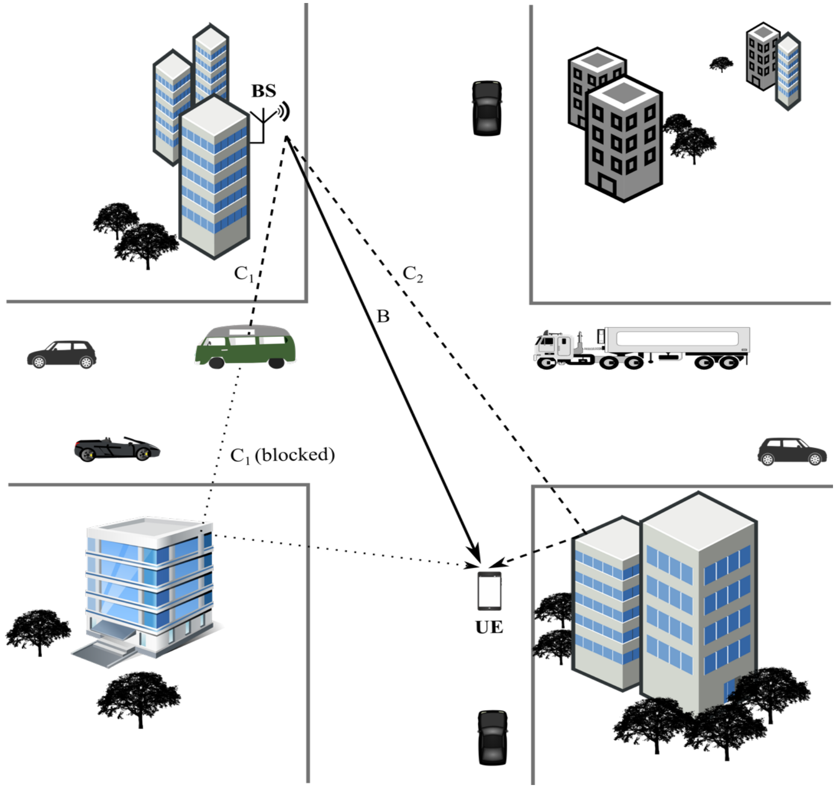

Fig. Downlink communication between a BS-UE pair in a dense urban environment. Dashed lines are non-specular paths, one of the paths is blocked by a vehicle.

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