FEC and its applications

A HISTORIC PERSPECTIVE

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Forward Error Correction Coding at COMSAT Labs

- Improve reliability of 9.6 kbps in-band data in 64 kbps Single Channel per Carrier (SCPC) channel over Intelsat
  - SCPC channel carriers 56 kbps PCM data with 8 kbps sync
  - We reduced the frame sync to 4 kbps, and used 4 kbps for sending parity check bits
  - A rate 15/16 Hamming code does, with very straightforward circuit modification did the job
- 140 Mbps Transoceanic link over a 72-Mbps Intelsat transponder
  - Needed to deliver more than 2.33 bit/symbol at 60 Msym/s symbol rate
  - Used 8-PSK and rate 7/9 convolutional code with Viterbi decoding
  - Initial attempt used 16 ECL MCM made ourselves, but proved too difficult to manufacture
  - Accomplished eventually with FPGA replacing the MCM to accomplished job later
  - Even extended to 200 Mbps for NASA

Era of Turbo Codes

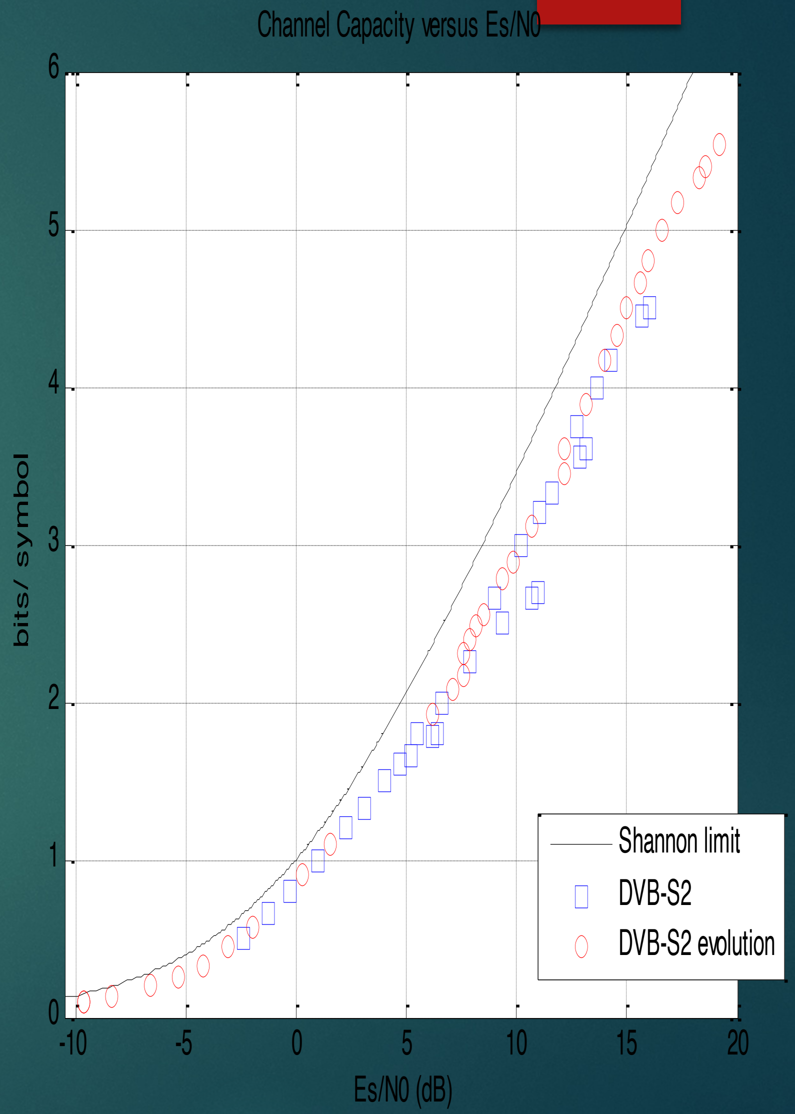
- Turbo codes were discovered in the early 90's, it was found to perform significantly better than the state-of-the-art at the time (convolutional codes with soft-decision decoding used since the 60s)
  - Require 2.5-3 dB less power to send the same amount of information.
  - While decoding is more complicated, the encoder is still very simple
  - Immediately identified as a way to double the VSAT return channel speed as they had been uplink power limited
    - 64 kbps → 128 kbps, 128 kbps → 256 kbps, etc.
- Given its success in the satellite channels, we introduced it to the 3rd Generation (3G) Wireless standards
  - Overcame initial skepticism of the wireless industry showing 2 dB better performance in the multipath fading channel compared to the IS-95 (CDMA) K=9 convolutions codes
  - Accepted first in the TIA and later in 3GPP for 3rd Generation; even carried over to 4G LTE.
- An example for "***Satellite Industry Leading the Way!***"

Era of Low-Density Parity Check Codes (LDPC)

- With turbo codes gaining acceptance in wireless industry, soft-decision decoding of LDPC based on Tanner Graph demonstrated potential to offer similar, or even slightly better performance
- Broadcast industry began to transition into HDTV, gave Direct to Home (DTH) satellite broadcasters a motivation to consider change the set-top-boxes, initiated the DVB-S2 effort, possibly taking advantage of the coding advancements
- The goal is to be as close to Shannon capacity as possible, only to be constrained by practical modulation and implementation complexity
- Several things we knew at the time:
  - Code block (or interleaver size for turbo codes) must be as long as practical
  - Block length can be multiples of all small integers to adapt to almost all code rates and all modulations
  - Code must be sufficiently random to perform, yet some hidden structure for practical implementation of codecs needed
  - The decoding algorithm must be highly parallelizable to support high-speed implementation
- Both turbo and LDPC codes are strong candidates, but LDPC decodes are more parallelizable, neither do they have “error floor”
- After two rounds of competition, with 0.3 dB advantage over the runner up, the only LDPC candidate was selected over 7 other turbo code proposals as DVB-S2 standard

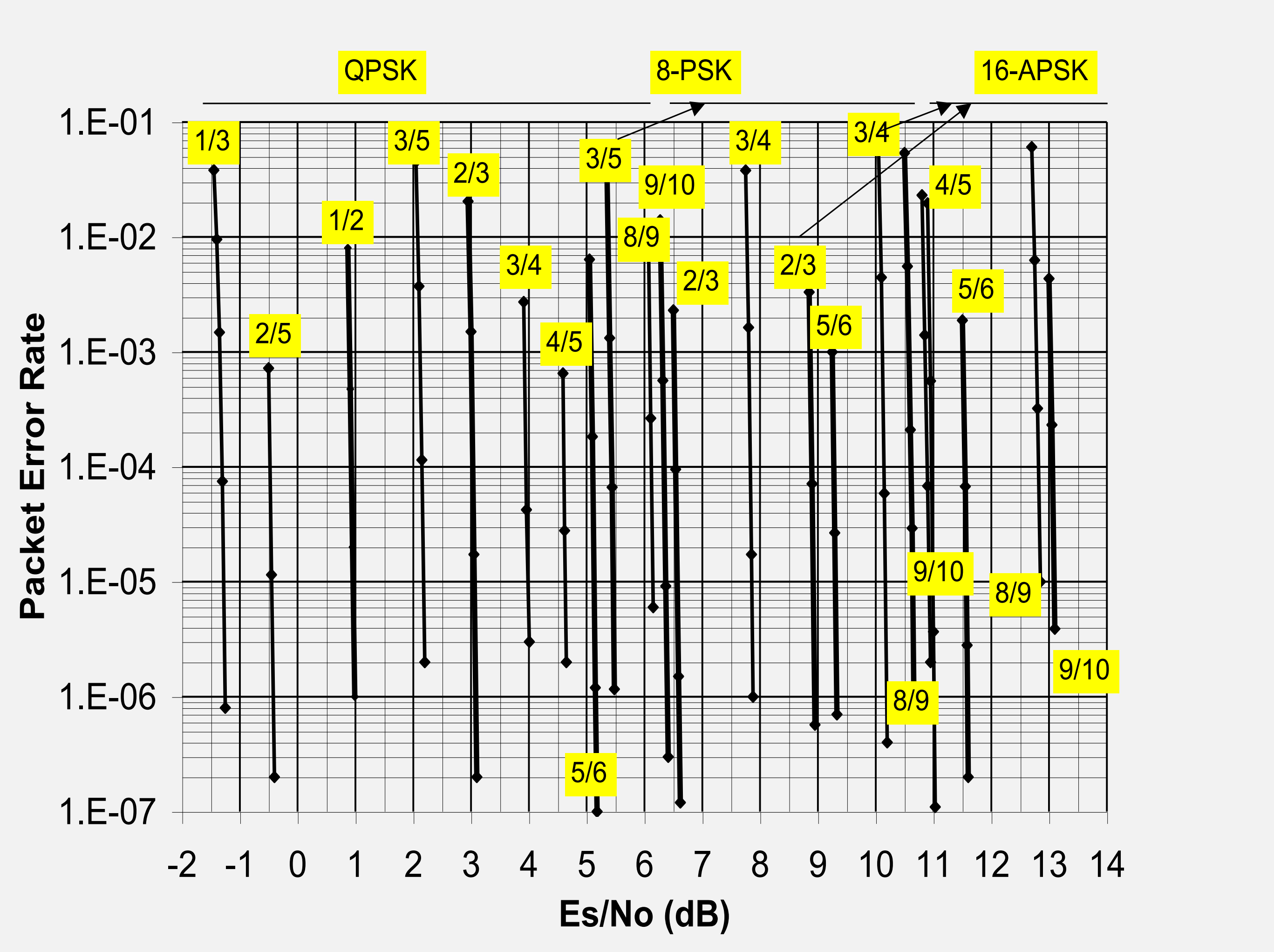
DVB-S2 and S2X

- In 2003, priority of satellite TV broadcasters is to achieve 2 b/sym with existing space and ground segment to carry HDTV (accomplished by 8-PSK modulation at rate 2/3) included 16-APSK and 32-APSK for future
- DVB-S2 is the first major standard selected LDPC, almost all major wireless standards after DVB-S2 adopted LDPC since
  - WiMax and WiFi (IEEE802.11.n), and now 5G New Radio (NR), etc.
  - Another example of "***Satellite Industry leading the Way***"
- In 2013, DVB decided to fill all the intermediated code rates, extend the upper end to include 64-,128- and 256-APSK. In addition, we added VLSNR mode to extend the lower end to -10 dB Es/No.
- VLSNR goal is to support terminals in deep fades, for small/mobile terminals to receive limited information from a broadcast carrier
  - The terminal will not be able to receive other information in the carrier, i.e. only "bursts" or "frames" modulated and coded in VLSNR format
    - Not expected to be the main use for the operator, due to its low BW efficiency



Lessons of DVB-S2/S2X

- ***Shannon is right!*** - Infinitely reliable communications can be established at rates at or below the capacity
- Gone are the "***waterfalls***", only "***thresholds***" remain – 0.2 dB makes the difference between night and day
  - It is possible to achieve one error event per day or even lower
- Good measurement of received Es/No is required to implement Adaptive Code Modulation (ACM), to maximize throughput and maintain reliable communication
  - DVB-S2X reduces the granularity between modcod to about 0.3 dB, about the limit of practical implementation accuracy



Looking forward

- Very small room for improvement to DVB-S2/S2X allowed by Shannon, even though further simplification of the decoder implementation and increase in decoder speed may still possible
- There are still room to design codes for "Multiple Access Channels", where aggregated transmit power is greater than each of the single transmitter, thus greater capacity is achievable per Shannon
- We designed a set of multiple access FEC codes to be used for Non-Orthogonal Multiple Access (NOMA) and submitted to 3GPP during the 5G standardization process
  - The wireless industry were unable to reach consensus, neither were they willing to reopen FEC coding discussions. NOMA was one of the most innovative ideas in 5G, but failed to be included in the standard
  - We actually implemented an early version of the scheme in our current VSAT networks, and enjoyed the expected benefit of NOMA
  - "***Satellite Industry is still Leading the Way", terrestrial wireless may eventually join***!!