32APSK narrowband modem for the QO-100 GEO amateur radio transponder

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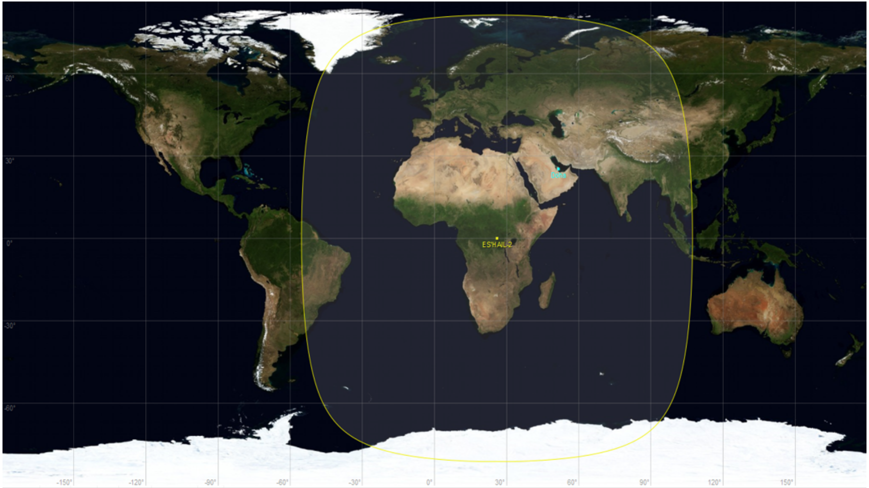
The QO-100 payload on Es’hail 2

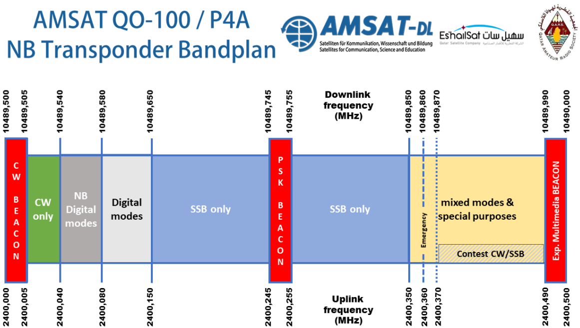
- Es’hail 2 is the 2nd GEO TV satellite from the Qatari company Es’hailSat. Launched on November 2018.
- It carriers the first (and only) amateur radio GEO payload, due to a collaboration from QARS and AMSAT-DL. Active since February 2019.
- The amateur transponder is 2.4 GHz up and 10.5 GHz down
- Groundstations use inexpensive Ku-band COTS LNBs for RX and modified UMTS (2.1 GHz) or WiFi PAs for transmit

The footprint of Es'hail 2



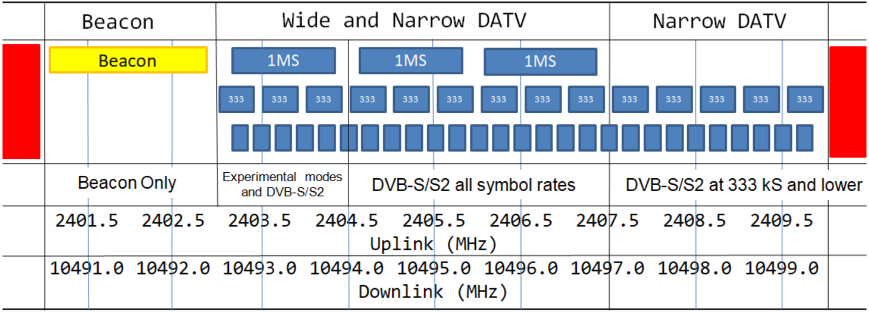
The NB and WB transponders

- QO-100 actually has two bent-pipe transponders
- The narrowband (NB) transponder is 500 kHz wide
- Signals can be up to 2.7 kHz wide, and not stronger than the beacon
- Usage similar to an HF band



The NB and WB transponders

- The wideband (WB) transponder is mainly intended for Digital TV using DVB-S2
- It is 9 MHz wide (1.5 MHz used up by the beacon), and supports several “channels” depending on the bandwidth



QO-100 as a playground for experimentation

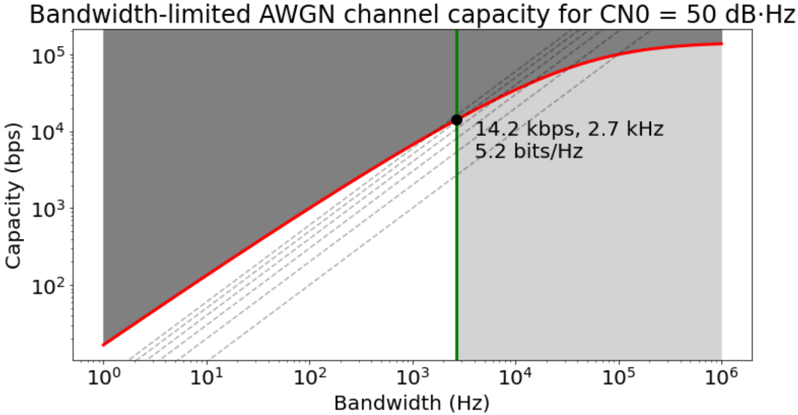
- A GEO transponder provides unique opportunities for experimentation: a channel with large geographical coverage and 24/7 propagation
- Some experiments and developments that have been enabled by QO-100:
  - DVB-S2
  - Narrowband digital communications
  - High altitude balloon tracker (by DL7AD, using Olivia 2/125)
  - Low SNR FT8 (by AMSAT-Brazil)
  - LoRa
  - PN ranging (myself)
  - Frequency measurement
  - Relay of a FUNcube-1 groundstation data from Antarctica

QO-100 as a playground for experimentation

- But yet a lot could be done to realize its full potential. Some ideas:
  - Machine-to-machine communications
  - IP traffic
  - Spread spectrum
  - New PHYs
  - Very low power communications
  - LEO satellites
  - You name it!
- Don't get me wrong. Some great things have been done with QO-100, but most of its use is really "conventional" (SSB, CW, the same digital modes that existed for HF, and DVB-S2)
- Doing novel things is tricky: often, lots of time and some expertise required

An idea for a digital modem for the NB transponder

- Signals in the NB transponder should be not stronger than the beacon (∼50 dB·Hz CN0) and at most 2.7 kHz bandwidth ⇒ severely bandwidth limited!

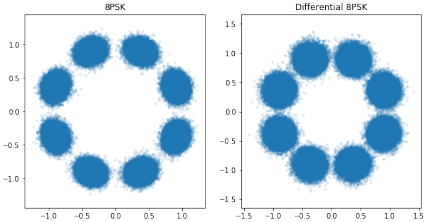


An idea for a digital modem for the NB transponder

- The constraints of 50 dB·Hz CN0 and 2.7 kHz banwdith probably wouldn't make sense in a professional/commercial project
- In an amateur setting they are still arguable
- I like to see these constraints as an engineering exercise from which original solutions can appear
- The goal: try to cram in as much data rate within these constraints
- Perhaps no real practical application for this (communications are much simpler in a 125 ksym channel of the WB transponder)
- The problem provides its own set of unique rabbit holes to dig in and learn

Some previous work

- My experiments with 54 dB·Hz CN0 2kbaud 8PSK in December 2019



- Kurt Moraw DJ0ABR's Multimedia High Speed Modem (different modes up to 8PSK at 2400 baud; Reed-Solomon FEC). December 2020.
  `https://wiki.amsat-dl.org/doku.php?id=en:hsmodem:start`

A new idea: 32APSK

- New idea starting in May 2021. Don't be conservative. Really try to cram in as much bits/Hz as possible.
- Project progressing slowly. Favour more advanced solutions even if they require more development time.
- Design criteria:
  - Target 50 dB·Hz CN0 and 2.7 kHz bandwidth
  - Assume groundstations use good hardware (SDRs, stable frequency references)
  - Modem latency not too large (100's of ms; comparable to GEO round-trip-time)
  - Long transmissions with a continous carrier. Receiver able to synchronize within 100's of ms.
- Draw lots of ideas from DVB-S2. But some are not at all applicable, due to the low bandwidth (symbol rate)
- Challenge: frequency stability of the 10.5 GHz RX

Modem waveform

- Single-carrier APSK waveform
- RRC filter with 5% excess bandwidth (the minimum supported by DVB-S2X). Long filters need to be designed carefully.
- Symbol rate 2570 baud $\Rightarrow$ 2698.5 Hz bandwidth

Data constellation

- 50 dB·Hz CN0 and 2570 baud give 15.9 Es/N0

Table 13: E_s/No performance at Quasi Error Free PER = 10^{-7} (AWGN channel)

Mode	Spectral efficiency	Ideal E_s/No (dB) for FECFRAME length = 64 800
QPSK 1/4	0,490243	-2,35
QPSK 1/3	0,656448	-1,24
QPSK 2/5	0,789412	-0,30
QPSK 1/2	0,988858	1,00
[illegible]	[illegible]	[illegible]
16APSK 8/9	3,523143	12,89
16APSK 9/10	3,567342	13,13
32APSK 3/4	3,703295	12,73
32APSK 4/5	3,951571	13,64
32APSK 5/6	4,119540	14,28
32APSK 8/9	4,397854	15,69
32APSK 9/10	4,453027	16,05

- 32APSK 8/9 is probably the best candidate

32APSK constellation

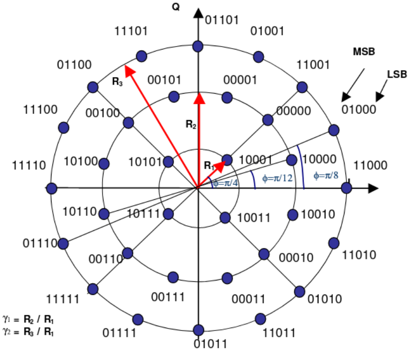


Figure 12: 32APSK signal constellation

Table 10: optimum constellation radius ratios γ_1 and γ_2 (linear channel) for 32 APSK

Code rate	Modulation/coding spectral efficiency	γ_1	γ_2
3/4	3,74	2,84	5,27
4/5	3,99	2,72	4,87
5/6	4,15	2,64	4,64
8/9	4,43	2,54	4,33
9/10	4,49	2,53	4,30

64APSK from DVB-S2X

- 64APSK with lower coding rate is also an interesting idea. Not yet tested. Probably risky due to phase noise

Canonical MODCOD name	Spectral efficiency [bit/symbol] (note 4)	Ideal E_s/N_0 [dB] for (AWGN Linear Channel) (note 1)
64APSK 32/45-L	4,206428	13,98
64APSK 11/15	4,338659	14,81
64APSK 7/9	4,603122	15,47
64APSK 4/5	4,735354	15,87
64APSK 5/6	4,936639	16,55
128APSK 3/4	5,163248	17,73
128APSK 7/9	5,355556	18,53

- There are three 64APSK constellations in DVB-S2X: 16+16+16+16 (for 32/45-L), 8+16+20+20 (for 7/9, 4/5, and 5/6), and 4+12+20+28 (for 11/15)

Synchronization

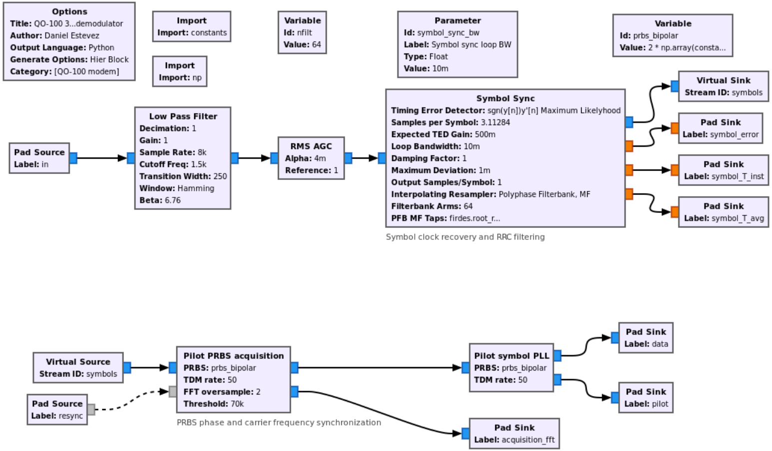
- Carrier phase recovery is much more difficult than DVB-S2 at high symbol rates
- Channel coherence time $\sim$100 ms. A PLL with bandwidth 10-25 Hz can track this.
- There is more than enough SNR for phase tracking: spending only 34 dB·Hz CN0 we have more than 20 dB loop bandwidth.
- But symbols are very long: the channel coherence is only $\sim$250 symbols. The phase synchronization tools of DVB-S2 are not applicable.
- Possible approaches:
  - Residual-carrier type: a constant CW carrier
  - Pilot symbols in TDM
- Final solution: Use a pilot symbol every 50 symbols (gives 51.4 pilot symbols / second)

Synchronization

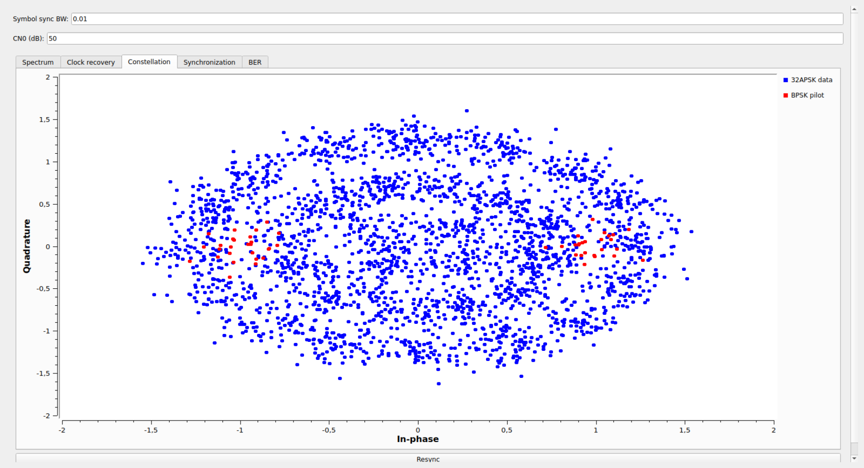
- The pilot symbols are BPSK modulated with a 31 symbol m-sequence
- The sequence repeats every 603 ms
- This can be used for frame synchronization
- The receiver detects the pilot sequence using circular correlation
- Also useful for initial carrier frequency offset acquisition (sub-Hz resolution).
- Note that initial carrier frequency offset needs to be less than 25 Hz (easy to tune by hand or with band-edge open loop estimate)

GNU Radio implementation

- A transceiver for this modem was implemented in GNU Radio using custom C++ blocks for simulated and over-the-air tests

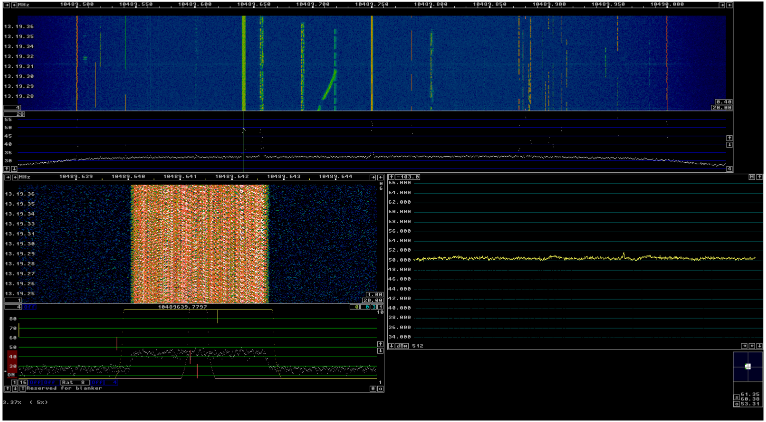


GNU Radio implementation



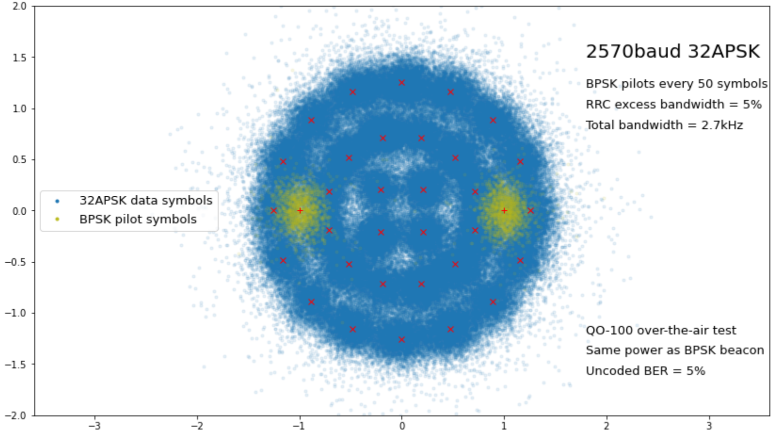
Over-the-air tests

- Some over-the-air tests have been done through the QO-100 transponder to validate the waveform design and receiver implementation



Over-the-air tests

- The IQ recordings and results of the tests are available online
- Uncoded BER was around 5%



FEC design: LDPC

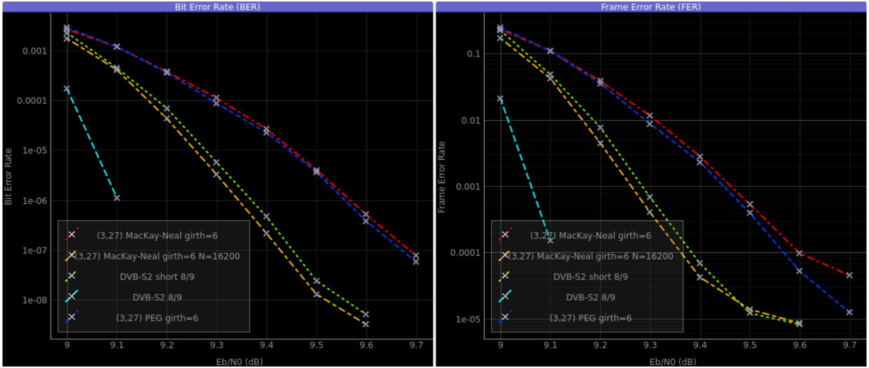
- The synchronization BPSK sequence gives a natural FEC frame size of 7595 bits
- DVB-S2 LDPC codewords are much longer: 64800 bits and 16200 bits
- Try to design an $r = 8/9$ code that gives good results at 9.42 Eb/N0 with 32APSK. Still work in progress.
- Many references explain how to implement LDPC decoders. Not many explain how to design your own code. Main reference: Sarah Jonshon, “Iterative Error Correction”
- Use AFF3CT for simulation
- Pseudorandom constructions work well for moderate and large code sizes, but code structure is important
- We do not care much about computational cost (bitrate is low)

ldpc-toolbox

- Developed a small CLI tool and library in Rust called ldpc-toolbox to assist in designing LDPC codes
- Sparse matrix implementation with routines such as computing girth and alist format output
- Supports MacKay-Neal and PEG (progressive edge growth) pseudorandom constructions
- Can build parity check matrices for all the DVB-S2 codes
- `https://crates.io/crates/ldpc-toolbox`

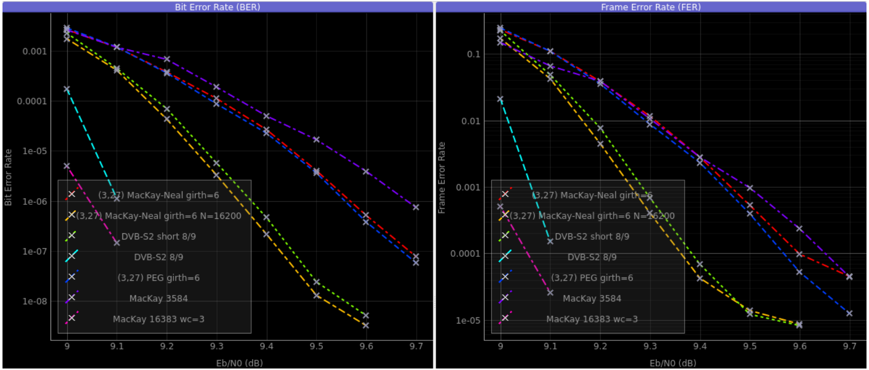
LDPC code comparison

- The frame size of only 7595 bits reduces performance
- MacKay-Neal and PEG constructions are giving results comparable to the DVB-S2 IRA codes



MacKay's encyclopedia of codes

- But wait! There are much better codes
- MacKay made an encyclopedia with assorted LDPCs `http://www.inference.org.uk/mackay/codes/data.html`
- But what's the secret sauce?



References

- https://destevez.net/2021/05/32apsk-narrowband-modem-for-qo-100/
- https://destevez.net/2021/07/ldpc-code-design-for-my-qo-100-narrowband-modem/