Variable Coded Modulation (VCM) with AR4JA/C2 LDPC Codes

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Bandwidth Efficiency vs. Power Efficiency

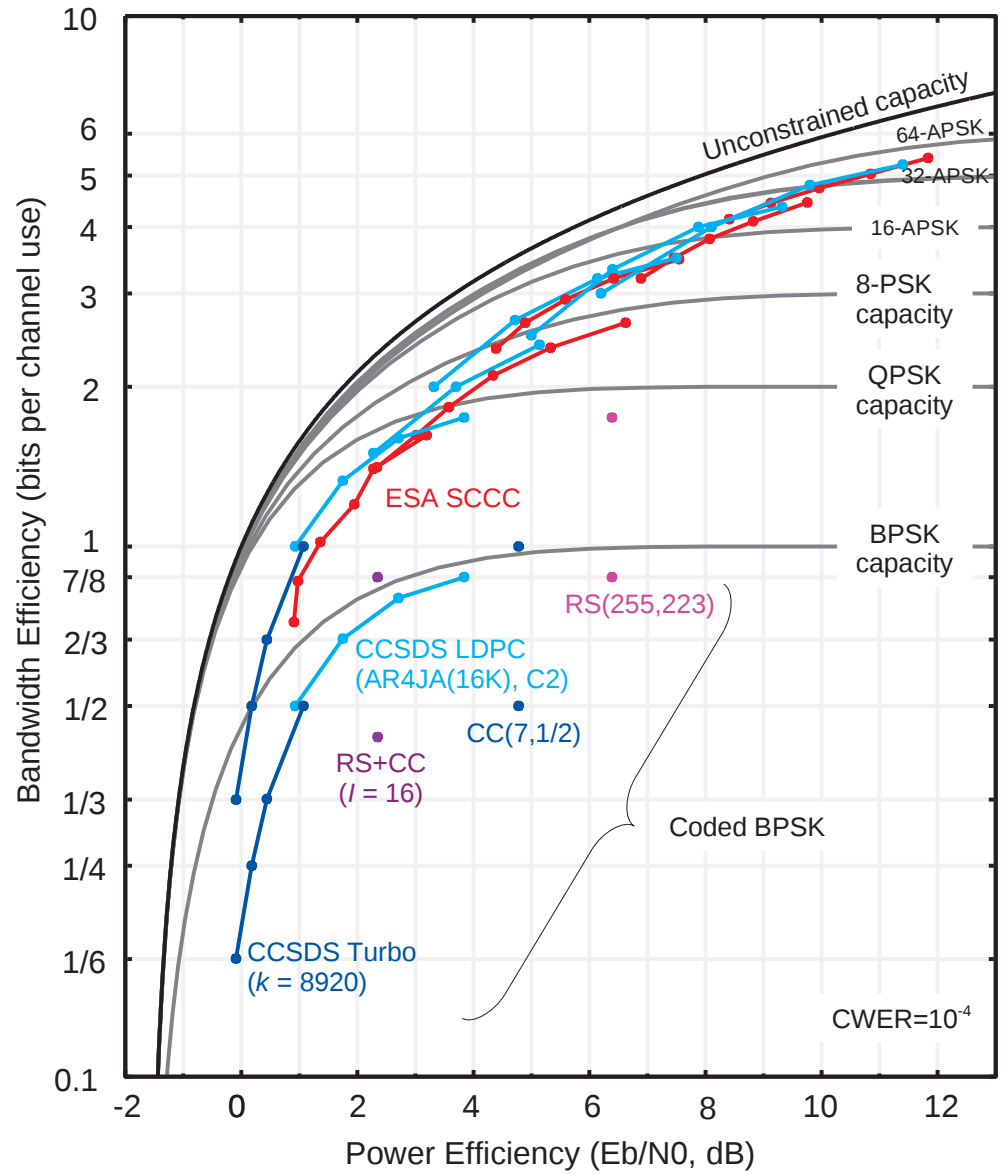
Shown on plot:

- Constrained and unconstrained capacity
- Coded BPSK, QPSK, 8-PSK, 16-APSK, 32-APSK, 64-APSK, at CWER=10^{-4}:
  - CCSDS (AR4JA, C2) LDPC (light blue) [2,3]
  - ESA SCCC (red) [4]
  - CCSDS turbo (blue) [1,2]
  - CC, RS, RS+CC (blue, magenta, purple) [1,2]

Observations

- LDPC codes are natural extension of Turbo codes to higher bandwidth efficiencies
- The SCCC and LDPC codes heavily overlap in their utility (achievable operating point in the trade-space)
- The LDPC codes outperform the SCCC codes, by up to 0.75 dB (e.g., at 2 b/c.u.), despite their shorter length

Based on this, we expect LDPC and SCCC to perform similarly when used with Variable Coded Modulation (VCM)



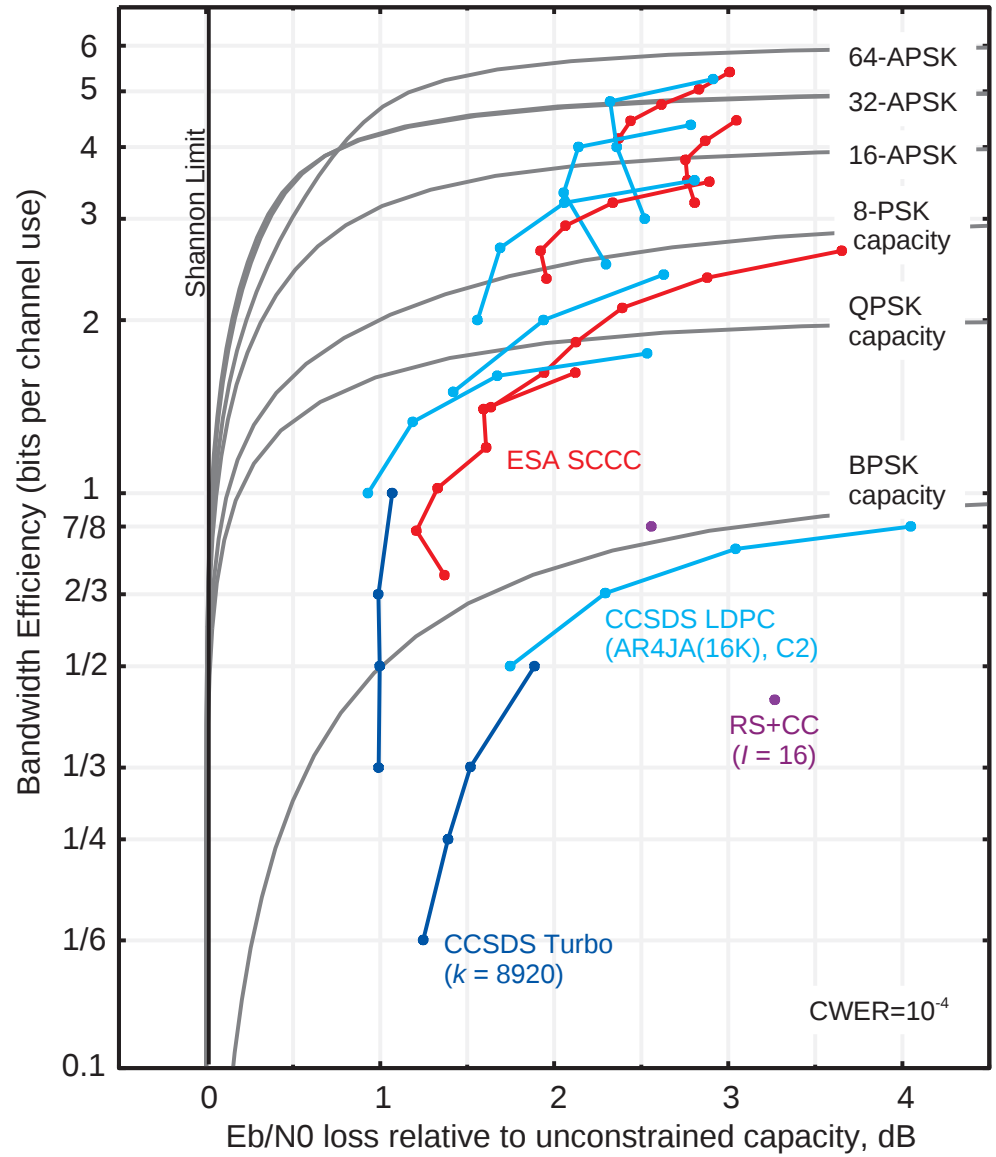
Gap to Capacity: Code Imperfectness

Same data, shown as "gap" to capacity

- Shows the additional Eb/N0 the coded modulations need relative to perfect, unbounded-length coding and unconstrained modulation.

Observations

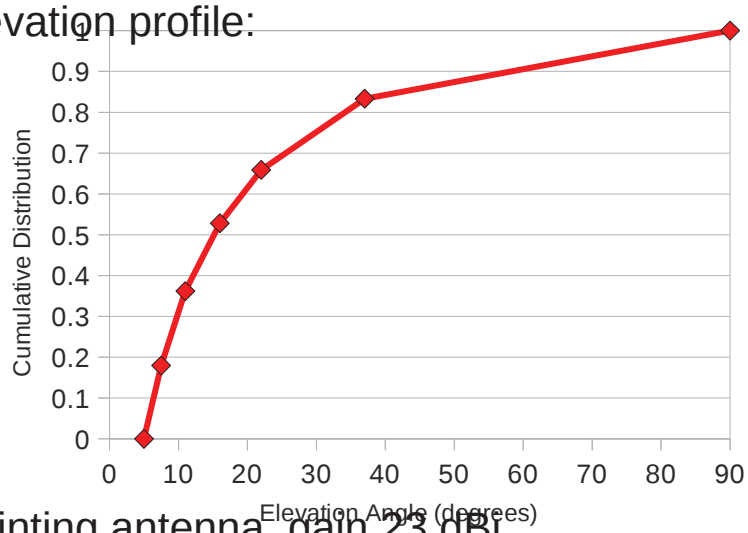
- On modulation capacities (gray):
  - BPSK has >1 dB loss for rates > 1/2
  - All have brick wall at 0 dB – they are optimal at asymptotically low rate
  - 64-APSK has design flaw – it's worse than 32-APSK below 4 b/c.u.
- On coded modulations (colored)
  - Turbo+QPSK gap: about 1.0 dB
  - SCCCs with 16/32/64-APSK have a capacity gap of 2+ dB; the 32-APSK performance appears to have a design problem
  - CCSDS LDPC is better, but only by about 0.5 dB at 16-APSK, and by about 1.5 dB at 32-APSK.
  - At >1.5 b/c.u., all codes have >1.5 dB gap!



Variable Coded Modulation (VCM) Example

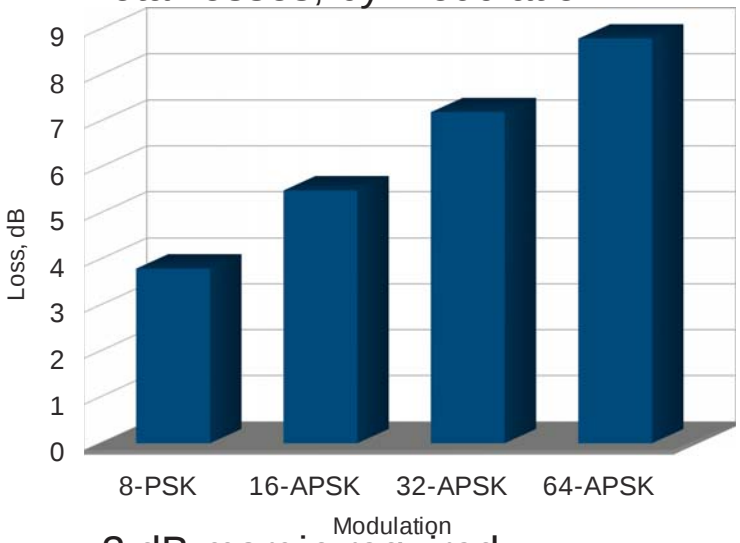
ESA described a practical scenario [5]:

- LEO satellite
  - Polar orbit at 693 km
  - Elevation profile:



  - Pointing antenna, gain 23 dBi
  - 60W TWTA – 27 GHz
  - TX power: 27.5W
  - Constant baud rate: 400 Msps
- Ground:
  - 6m antenna
  - ***G/T varies by elevation profile***

- Impairments:
  - Non-linear distortion: TWTA
  - Group delay distortion
  - Filter losses
  - Phase noise, I/Q imbalance
- Total losses, by modulation:



3 dB margin required

VCM Example: with SCCC

VCM with SCCC [5]:

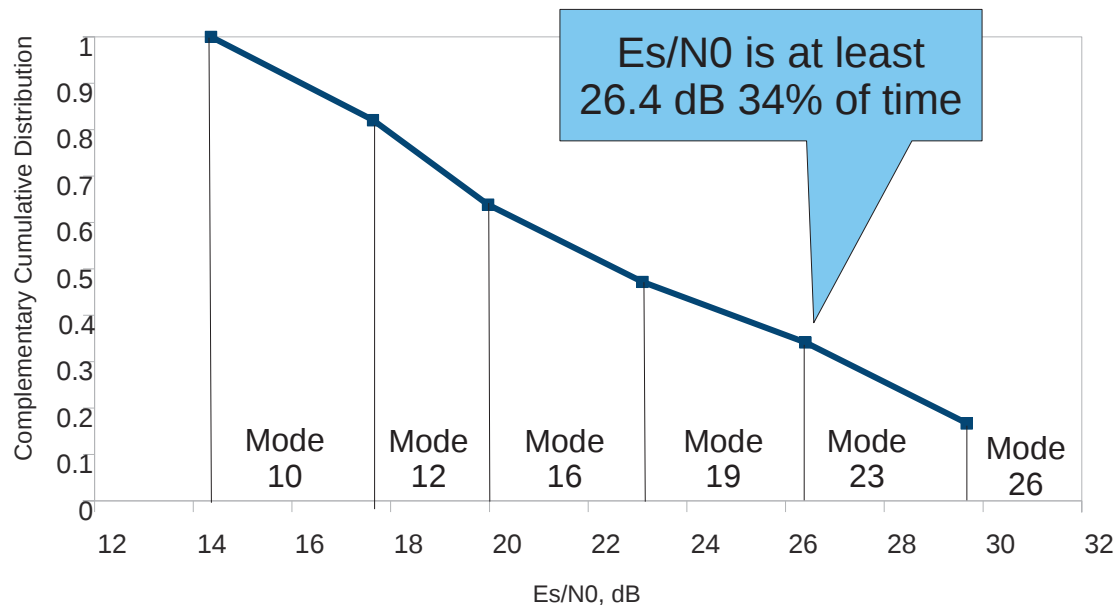
Section	Mode	Modulation	Bits per Channel use	Data Rate (Mbps)	Ideal Required Eb/N0 (dB) @CWER=1e-4	Ideal Required Es/N0 (dB) @CWER=1e-4	Margin (dB)	Losses (dB)	Required Es/N0 (dB), With margin And losses	Percent Time
1	10	8-PSK	2.10	841	4.33	7.56	3	3.8	14.36	17.96%
2	12	8-PSK	2.64	1055	6.63	10.84	3	3.8	17.64	18.21%
3	16	16-APSK	3.20	1280	6.42	11.47	3	5.5	19.97	16.65%
4	19	32-APSK	3.50	1398	7.46	12.90	3	7.2	23.10	13.06%
5	23	64-APSK	4.12	1647	8.47	14.62	3	8.8	26.42	17.45%
6	26	64-APSK	5.07	2027	10.82	17.87	3	8.8	29.67	16.67%

Average throughput: 1.364 Gbps

This is the corresponding Es/N0 profile:

E.g., SCCC mode 23:

Required Es/N0: 14.6 dB
(ideal, @ CWER=10^{-4})
Impairments: 8.8 dB
Margin: 3.0 dB
Required Es/N0: 26.4 dB



VCM Example: SCCC vs. NASA LDPC Codes

VCM with SCCC [5]:

Section	Mode	Modulation	Bits per Channel use	Data Rate (Mbps)	Ideal Required Eb/N0 (dB) @CWER=1e-4	Ideal Required Es/N0 (dB) @CWER=1e-4	Margin (dB)	Losses (dB)	Required Es/N0 (dB), With margin And losses	Percent Time
1	10	8-PSK	2.10	841	4.33	7.56	3	3.8	14.36	17.96%
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6	26	64-APSK	5.07	2027	10.82	17.87	3	8.8	29.67	16.67%

Average throughput: 1.364 Gbps

VCM with CCSDS LDPC (AR4JA, C2) codes, using same Es/N0 profile and 6 sections:

Section	Mode	Code	Modulation	Bits per Channel use	Data Rate (Mbps)	Ideal Required Eb/N0 (dB) @CWER=1e-4	Ideal Required Es/N0 (dB) @CWER=1e-4	Margin (dB)	Losses (dB)	Required Es/N0 (dB), With margin And losses	Percent Time
1	10	AR4JA(16K,2/3)	8-PSK	2.00	800	3.70	6.71	3	3.8	13.51	17.10%
2	14	AR4JA(16K,2/3)	16-APSK	2.67	1067	4.72	8.98	3	5.5	17.48	16.89%
3	15	AR4JA(16K,4/5)	16-APSK	3.20	1280	6.14	11.19	3	5.5	19.69	10.00%
4	16	C2	16-APSK	3.50	1399	7.50	12.94	3	5.5	21.44	19.96%
5	20	C2	32-APSK	4.37	1749	9.32	15.73	3	7.2	25.93	23.37%
6	24	C2	64-APSK	5.25	2099	11.40	18.60	3	8.8	30.40	12.69%

Average throughput: 1.399 Gbps

VCM Frame Descriptor

VCM "Frame descriptor" for SCCC [5] specifies which of 27 ACM formats is used:

Bit Number	Content
b_1-b_5	ACM Formats (Decimal values 1 to 27 are used with bit b_1 being the most significant bit)
b_6	Distributed Pilot On (=1) / Off (=0)
b_7	Reserved (set to 0)

The bits b1 – b5 could easily be extended or redefined to refer to other CCSDS codes.

Conclusions

- SCCC and LDPC are similar in many practical ways:
  - Code rates (SCCC 0.36 to 0.9, LDPC: 0.5 to 0.875)
  - Blocklengths (SCCC 5758 to 43678, LDPC: 1024 to 16384)
  - Both can be used with higher order modulations
  - Bandwidth/power efficiency performance (LDPC is a few tenths of a dB better)
- For a practical example, VCM+LDPC performs similar to VCM+SCCC
- The SCCC Red Book could serve as a baseline for a more general CCSDS VCM protocol that can be applied to any of the CCSDS codes.

References

[1] "TM synchronization and channel coding – Summary of concept and rationale," CCSDS 130.1-G-1 Green Book, June 2006.

[2] "TM synchronization and channel coding," CCSDS 131.0-B-2 Blue Book, Aug. 2011.

[3] J. Hamkins, "Performance of low-density parity-check coded modulation," Proceedings of the Aerospace Conference, Big Sky, MT, Mar. 2010.

[4] "Flexible advanced coding and modulation scheme for high rate telemetry applications," CCSDS 131.0-R draft Red Book, September 2009.

[5] M. Bertinelli, N. Toptsidis, P.-D. Arapoglu, "VCM performance for LEO satellites at 26 GHz," CCSDS presentation, May 3-7, 2010.

Backup

SCCC Performance Details

Mode	Modulation	Bits per Channel use	Data Rate (Mbps)	Ideal Required Eb/N0 (dB) @CWER=1e-4	Ideal Required Es/N0 (dB) @CWER=1e-4	Margin (dB)	Losses (dB)	Required Es/N0 (dB), With margin And losses
1	QPSK	0.71	284	0.96	-0.52	3	3	5.48
2	QPSK	0.86	344	0.98	0.32	3	3	6.32
3	QPSK	1.04	415	1.29	1.45	3	3	7.45
4	QPSK	1.21	486	1.90	2.74	3	3	8.74
5	QPSK	1.39	557	2.30	3.74	3	3	9.74
7	8-PSK	1.39	557	2.39	3.83	3	3.8	10.63
6	QPSK	1.63	652	3.17	5.29	3	3	11.29
8	8-PSK	1.63	652	2.99	5.11	3	3.8	11.91
9	8-PSK	1.84	735	3.56	6.20	3	3.8	13.00
10	8-PSK	2.10	841	4.33	7.56	3	3.8	14.36
11	8-PSK	2.37	948	5.33	9.08	3	3.8	15.88
13	16-APSK	2.37	948	4.37	8.12	3	5.5	16.62
14	16-APSK	2.64	1055	4.90	9.11	3	5.5	17.61
12	8-PSK	2.64	1055	6.63	10.84	3	3.8	17.64
15	16-APSK	2.90	1161	5.61	10.24	3	5.5	18.74
16	16-APSK	3.20	1280	6.42	11.47	3	5.5	19.97
17	16-APSK	3.50	1398	7.52	12.96	3	5.5	21.46
18	32-APSK	3.20	1280	6.89	11.94	3	7.2	22.14
19	32-APSK	3.50	1398	7.46	12.90	3	7.2	23.10
20	32-APSK	3.82	1529	8.04	13.87	3	7.2	24.07
21	32-APSK	4.12	1647	8.81	14.95	3	7.2	25.15
23	64-APSK	4.12	1647	8.47	14.62	3	8.8	26.42
22	32-APSK	4.44	1778	9.76	16.24	3	7.2	26.44
24	64-APSK	4.44	1778	9.13	15.61	3	8.8	27.41
25	64-APSK	4.77	1908	9.93	16.72	3	8.8	28.52
26	64-APSK	5.07	2027	10.82	17.87	3	8.8	29.67
27	64-APSK	5.39	2157	11.85	19.16	3	8.8	30.96

CCSDS LDPC Performance Details

Mode	Code	K	N	Code Rate	Modulation	Bits/ Symbol	Bits/ Channel Use	Ideal Required Eb/N0 (dB) @CWER=1e-4	Ideal Required Es/N0 (dB) @CWER=1e-4
1	AR4JA(16K,1/2)	16384	32768	0.50	BPSK	1	0.50	0.93	-2.08
2	AR4JA(16K,2/3)	16384	24576	0.67	BPSK	1	0.67	1.75	-0.01
3	AR4JA(16K,4/5)	16384	20480	0.80	BPSK	1	0.80	2.71	1.74
4	C2	7136	8160	0.87	BPSK	1	0.87	3.84	3.26
5	AR4JA(16K,1/2)	16384	32768	0.50	QPSK	2	1.00	0.93	0.93
6	AR4JA(16K,2/3)	16384	24576	0.67	QPSK	2	1.33	1.75	3.00
7	AR4JA(16K,4/5)	16384	20480	0.80	QPSK	2	1.60	2.71	4.75
8	C2	7136	8160	0.87	QPSK	2	1.75	3.84	6.27
9	AR4JA(16K,1/2)	16384	32768	0.50	8-PSK	3	1.50	2.28	4.04
10	AR4JA(16K,2/3)	16384	24576	0.67	8-PSK	3	2.00	3.7	6.71
11	AR4JA(16K,4/5)	16384	20480	0.80	8-PSK	3	2.40	5.14	8.94
12	C2	7136	8160	0.87	8-PSK	3	2.62	6.6	10.79
13	AR4JA(16K,1/2)	16384	32768	0.50	16-APSK	4	2.00	3.32	6.33
14	AR4JA(16K,2/3)	16384	24576	0.67	16-APSK	4	2.67	4.72	8.98
15	AR4JA(16K,4/5)	16384	20480	0.80	16-APSK	4	3.20	6.14	11.19
16	C2	7136	8160	0.87	16-APSK	4	3.50	7.5	12.94
17	AR4JA(16K,1/2)	16384	32768	0.50	32-APSK	5	2.50	5	8.98
18	AR4JA(16K,2/3)	16384	24576	0.67	32-APSK	5	3.33	6.4	11.63
19	AR4JA(16K,4/5)	16384	20480	0.80	32-APSK	5	4.00	7.88	13.90
20	C2	7136	8160	0.87	32-APSK	5	4.37	9.32	15.73
21	AR4JA(16K,1/2)	16384	32768	0.50	64-APSK	6	3.00	6.2	10.97
22	AR4JA(16K,2/3)	16384	24576	0.67	64-APSK	6	4.00	8.1	14.12
23	AR4JA(16K,4/5)	16384	20480	0.80	64-APSK	6	4.80	9.8	16.61
24	C2	7136	8160	0.87	64-APSK	6	5.25	11.4	18.60