Digital Video Broadcasting By Satellite

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Outline

1. Satellite Television Standards
2. DVB-S2 Modulation
3. LDPC Coding
4. Tricks for Improving Performance
5. Conclusion

Outline

Digital Satellite Television in the United States

DirecTV

- Spinoff of Hughes Network Systems.
- Began operations in 1994.
- 12 geosynchronous satellites.
- 20 million U.S. subscribers at end of 2011.
- 23,000 employees in U.S. and Latin America.
- $33.4 billion market cap.

Dish Network.

- Spinoff of EchoStar.
- Began operations in 1996.
- 14 million U.S. subscribers in at end of 2011.
- 22,000 employees.
- $14.7 billion market cap.

The DVB Family

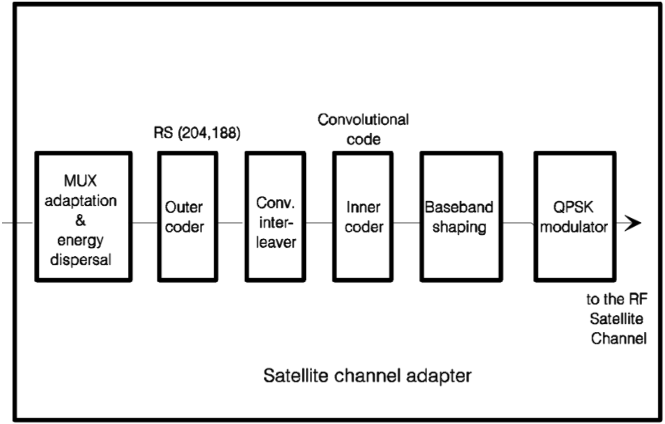
DVB is a family of open standards for digital video broadcasting.

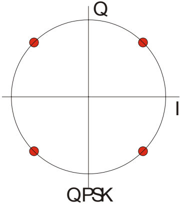
- Maintained by 270-member industry consortium.
- Published by ETSI.

Modes of transmission

- Satellite: DVB-S, DVB-S2, and DVB-SH
- Cable: DVB-C, DVB-C2
- Terrestrial: DVB-T, DVB-T2, DVB-H

DVB-S





- Modulation: QPSK with $\alpha = 0.35$ rolloff.
- Channel coding: Concatenated Reed Solomon and convolutional.

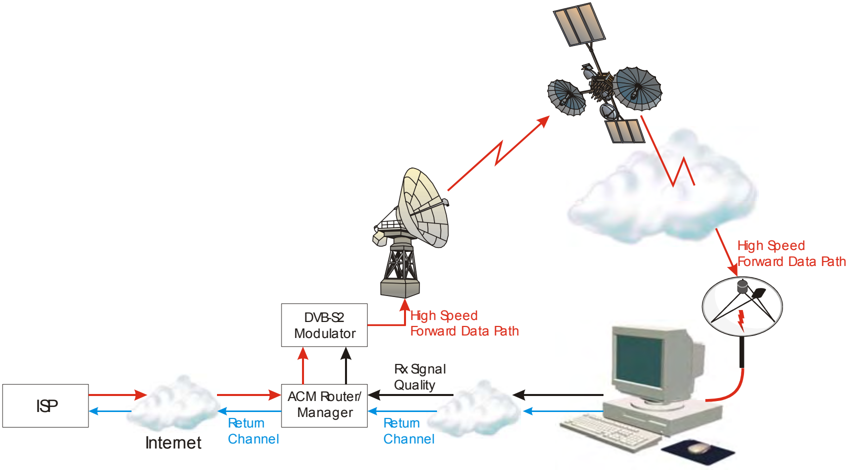
DVB-S2

DVB-S2 was introduced in 2003 with the following goals:

- Improve spectral efficiency by 30% through better modulation and coding.
    - Modulation: QPSK, 8PSK, 16/32 APSK.
    - Channel coding: LDPC with outer BCH code.
- Offer a more diverse range of services.
    - HDTV broadcast television.
    - Backhaul applications, e.g., electronic news gathering.
    - Internet downlink access.
    - Large-scale data content distribution, e.g., electronic newspapers.

Ratified 2005.

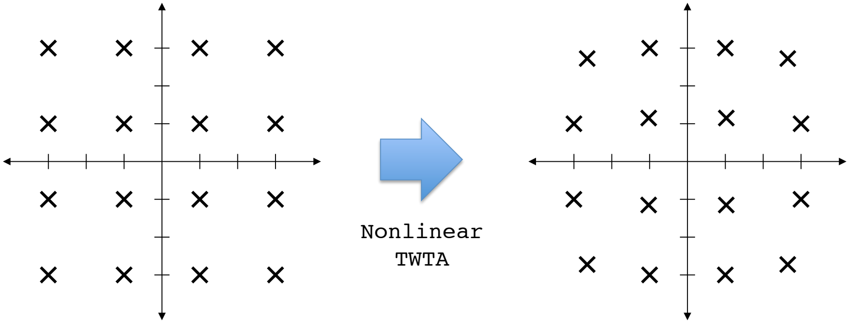
Adaptive Internet Downlink



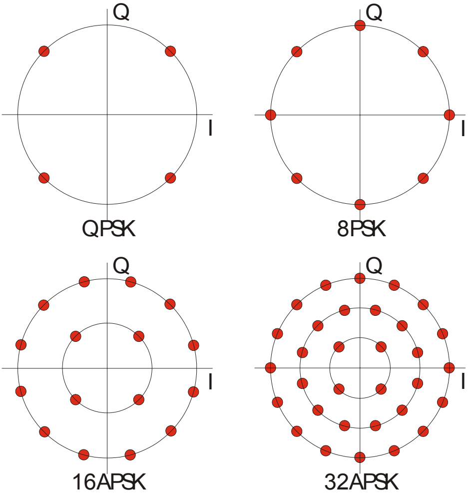
Outline

Why Not Use QAM?

- A constellation with $M = 2^m$ conveys m bits per channel use.
- Higher spectral-efficiencies require larger signal constellations.
- Nonlinear satellite channels are not well suited to square QAM.



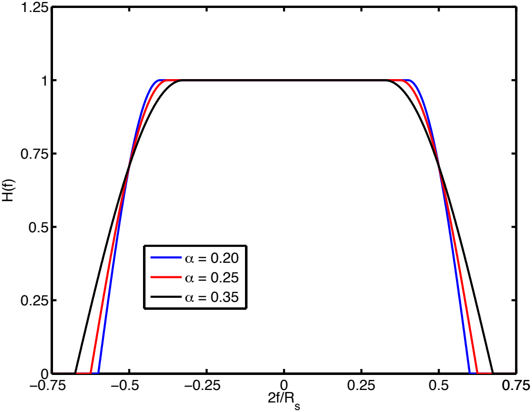
The DVB-S2 Signal Constellations



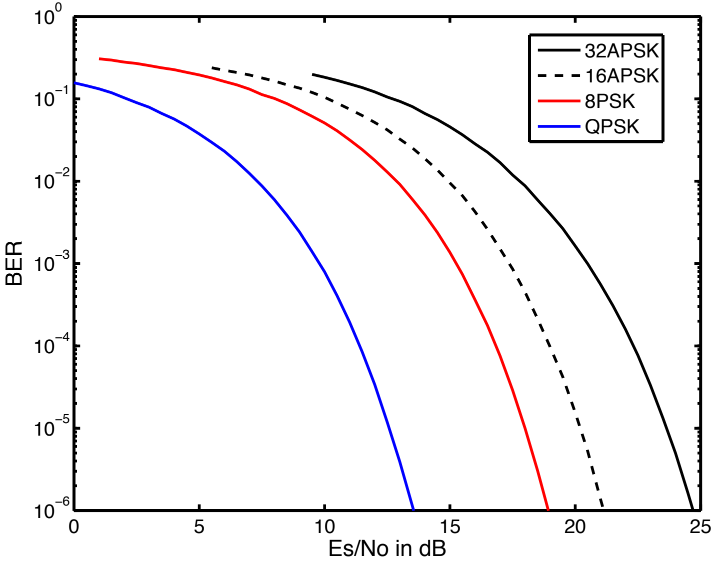
Raised-Cosine Rolloff Filtering

DVB-S2 uses a tighter root RC-rolloff filter.

- $B = R_s(1+\alpha)$
- Assuming a 6 MHz transponder channel...
- DVB-S Example:
  - $\alpha = 0.35.$
  - QPSK: $R_b = 2R_s$
  - $2(6)/(1.35) = 8.9$ Mbps
- DVB-S2 Example:
  - $\alpha = 0.20.$
  - 32-APSK: $R_b = 5R_s$
  - $5(6)/(1.2) = 25$ Mbps



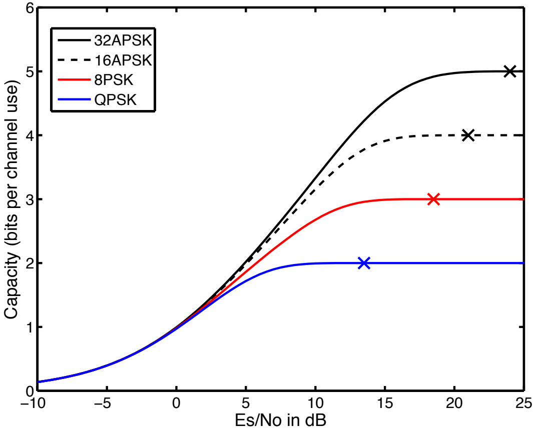
Uncoded BER in AWGN



Outline

Maximum Information Rate

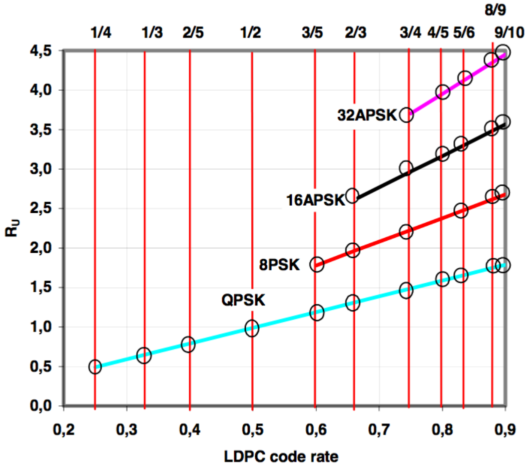
- Performance can be improved by using error control coding.
- Gains are limited by the modulation-constrained capacity.
- LDPC codes are capable of approaching capacity.



Symmetric information rate (assumes uniform input).

Available Code Rates

- The encoder maps length-k messages to length-n codewords.
- The code rate is $R = k/n$.
- Useful bit rate is $R_u = R \log_2(M)$.
- Two codeword lengths:
  - $16,200$.
  - $64,800$.



Coding by Example: Single Parity-Check Codes

- Consider the following rate $R = 5/6$ single parity-check code:

$$\mathbf{c} = [\underbrace{1 \quad 0 \quad 1 \quad 0 \quad 1}_{\mathbf{u}} \quad \underbrace{1}_{\text{parity bit}} \quad]$$

- One error in *any* position may be detected:

$$\mathbf{c} = \begin{bmatrix} 1 & 0 & X & 0 & 1 & 1 \end{bmatrix}$$

- Problem with using an SPC is that it can only detect a single error.

Product Codes

- Place data into a k by k rectangular array.
  - Encode each row with a SPC.
  - Encode each column with a SPC.
  - Result is a rate $R = k^2/(k+1)^2$ code.
- Example $k = 2$.

$c_1 = u_1$	$c_2 = u_2$	$c_3 = c_1 \oplus c_2$
$c_4 = u_3$	$c_5 = u_4$	$c_6 = c_4 \oplus c_5$
$c_7 = c_1 \oplus c_4$	$c_8 = c_2 \oplus c_5$	$c_9 = c_3 \oplus c_6$

=

1	0	1
1	1	0
0	1	1

- A single error can be corrected by detecting its row and column location

1	0	1
0	1	0
0	1	1

$\Rightarrow$

1	0	1
1	1	0
0	1	1

Linear Codes

$c_1 = u_1$	$c_2 = u_2$	$c_3 = c_1 \oplus c_2$
$c_4 = u_3$	$c_5 = u_4$	$c_6 = c_4 \oplus c_5$
$c_7 = c_1 \oplus c_4$	$c_8 = c_2 \oplus c_5$	$c_9 = c_3 \oplus c_6$

- The example product code is characterized by the set of five linearly-independent equations:

$$\begin{aligned}
c_3 = c_1 \oplus c_2 &\quad\Rightarrow\quad c_1 \oplus c_2 \oplus c_3 = 0 \\
c_6 = c_4 \oplus c_5 &\quad\Rightarrow\quad c_4 \oplus c_5 \oplus c_6 = 0 \\
c_7 = c_1 \oplus c_4 &\quad\Rightarrow\quad c_1 \oplus c_4 \oplus c_7 = 0 \\
c_8 = c_2 \oplus c_5 &\quad\Rightarrow\quad c_2 \oplus c_4 \oplus c_8 = 0 \\
c_9 = c_3 \oplus c_6 &\quad\Rightarrow\quad c_3 \oplus c_6 \oplus c_9 = 0
\end{aligned}$$

- In general, it takes $(n - k)$ linearly-independent equations to specify a *linear* code.

What is a Parity-Check Matrix?

- The system of equations may be expressed in matrix form as:

$$\mathbf{c}H^T = \mathbf{0}$$

where H is a *parity-check* matrix.

- Example:

$$\begin{array}{rcl} c_1 \oplus c_2 \oplus c_3 & = & 0 \\ c_4 \oplus c_5 \oplus c_6 & = & 0 \\ c_1 \oplus c_4 \oplus c_7 & = & 0 \\ c_2 \oplus c_4 \oplus c_8 & = & 0 \\ c_3 \oplus c_6 \oplus c_9 & = & 0 \end{array} \Leftrightarrow H = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

System of equations — Parity-check matrix

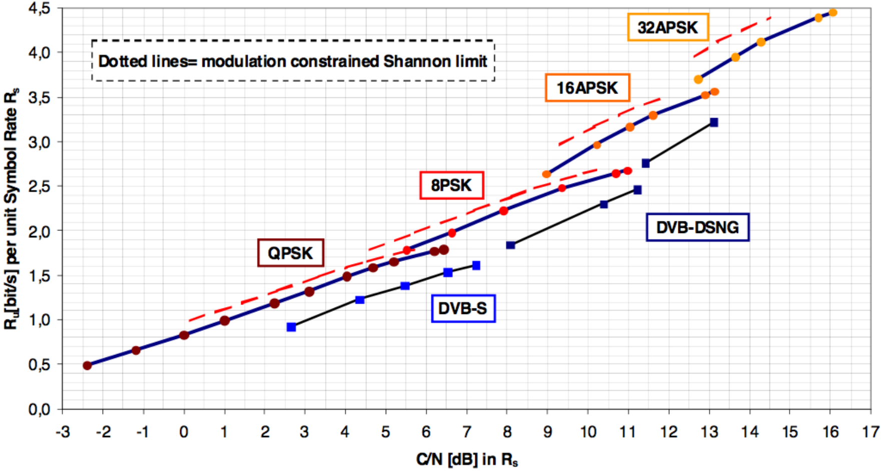
LDPC Codes

- An LDPC code is a code with a large, sparse H matrix.
- A code from MacKay and Neal (1996):

$$\mathbf{H} \quad = \quad \left[\begin{array}{cccc|cccc|cccc}
1 & & & & & 1 & & 1 & & 1 & & \\
1 & & & 1 & 1 & & & & & & 1 & \\
 & 1 & & & 1 & & 1 & & 1 & & & \\
 & & 1 & & & 1 & & & & & 1 & 1 \\
 & & 1 & & & & 1 & 1 & & & & 1 \\
 & 1 & & & 1 & & & & 1 & & 1 & \\
1 & & & 1 & & & 1 & & & 1 & & \\
 & 1 & & & & 1 & & 1 & & 1 & & \\
 & & 1 & 1 & & & & & 1 & & & 1
\end{array} \right]$$

- The code called a $(3, 4)$ *regular* code because:
    - Each column has exactly 3 ones.
    - Each row has exactly 4 ones.
- The DVB-S2 LDPC codes are *irregular*. More about this later.

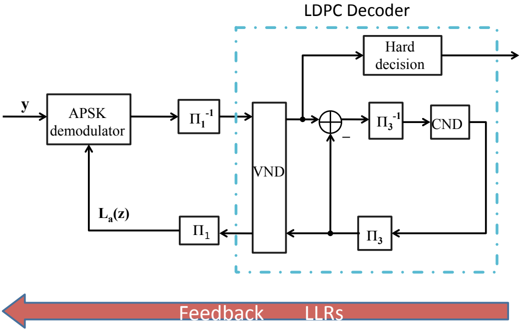
DVB-S2 vs. Shannon



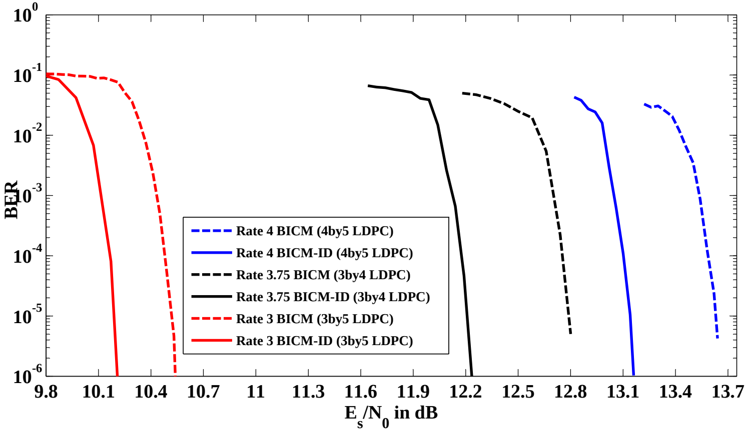
Outline

Iterative Demodulation and Decoding

- Conventional receivers first demodulation, then decode.
- Performance is improved by iterating between the demodulator and decoder.
- BICM-ID: bit-interleaved modulation with iterative decoding.



BICM vs. BICM-ID



Curves show performance of 32APSK in AWGN.

Constellation Shaping

- The symmetric information rate curves assume equiprobable signaling.
- It is possible to reduce the energy required to achieve a certain information rate by transmitting higher-energy signals less frequently than lower-energy signals.

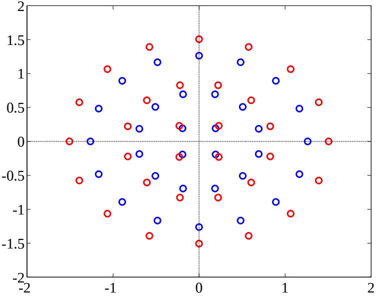


Figure: Uniform 32APSK o vs. shaped 32APSK o. Both constellations have the same energy.

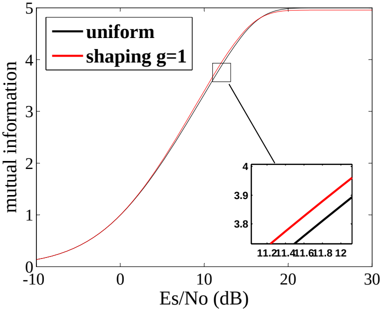


Figure: The capacity of shaped 32APSK is about 0.3 dB better than uniform 32APSK.

Sub-constellations

- The 32APSK is partitioned into two equal-sized sub-constellations.
- A *shaping bit* selects the sub-constellation, while the remaining bits select a symbol from the chosen sub-constellation.
- The lower-energy sub-constellation is selected more frequently.

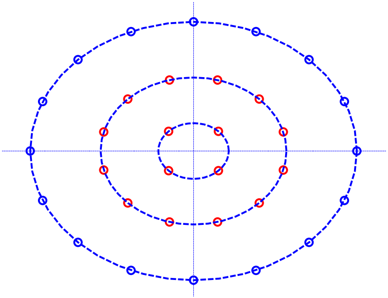


Figure: 32APSK w/ 2 sub-constellations

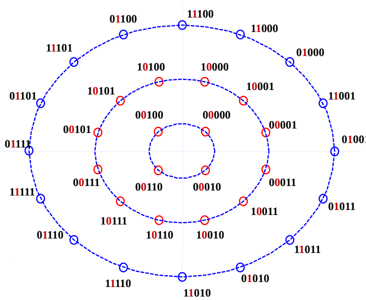


Figure: 32APSK symbol-labeling map

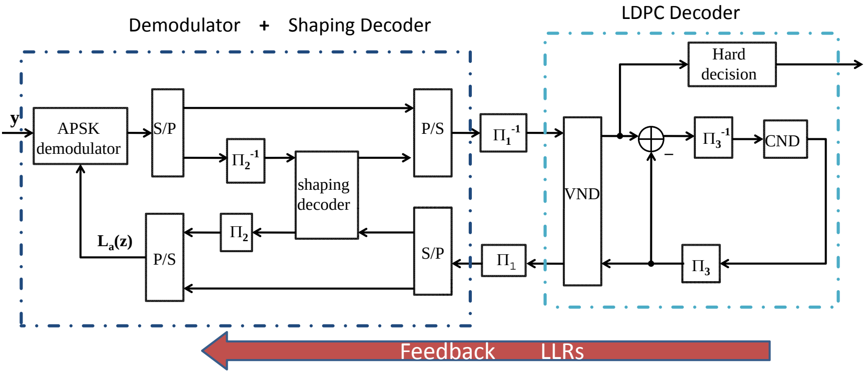
Shaping Encoder

- The shaping encoder should produce more zeros than ones.
- Example: $(n_s, k_s) = (5, 3)$

3 input data bits	5 output codeword bits
0 0 0	0 0 0 0 0
0 0 1	0 0 0 0 1
0 1 0	0 0 0 1 0
0 1 1	0 0 1 0 0
1 0 0	0 1 0 0 0
1 0 1	1 0 0 0 0
1 1 0	0 0 0 1 1
1 1 1	1 0 1 0 0

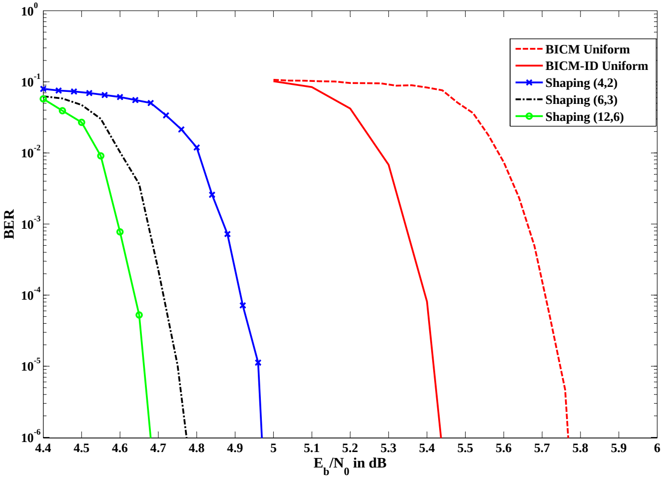
  - $p_0 = 31/40$: fraction of zeros.
  - $p_1 = 9/40$: fraction of ones.

Receiver Implementation



- Additional complexity relative to BICM-ID due to shaping decoder.
- MAP shaping decoder compares against all 2^{k_s} shaping codewords.

BER of Shaping in AWGN



- BER of 32-APSK in AWGN at rate R=3 bits/symbol.
- Code rates: $R_c = 3/5$ for uniform and $R_c = 2/3$ for shaped.

Irregular vs. Regular Codes

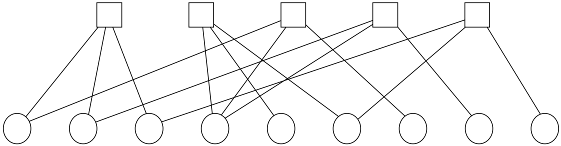
- An *irregular* LDPC code has columns with different *weights*.
  - The *Hamming weight* of a column is the number of 1's.
- An irregular code can outperform a regular code.
- The main design consideration is the *degree distribution*, which quantifies how many columns there are of a particular weight.
- The optimal degree distribution can be found through *linear programming*.
- The optimization takes into account the APSK modulation and shaping (if used).

Tanner Graphs

- The parity-check matrix may be represented by a *Tanner* graph.
- Bipartite graph:
  - Check nodes: Represent the $n-k$ parity-check equations.
  - Variable nodes: Represent the n code bits.
- If $H_{i,j}=1$, then i^{th} check node is connected to j^{th} variable node.
- Example: For the parity-check matrix:

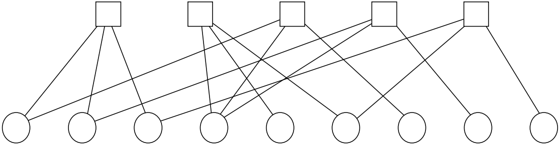
$$H = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

The Tanner Graph is:



Degree Distribution

- Edge-perspective degree distributions:
  - ρ_i is the fraction of *edges* touching degree i check nodes.
  - λ_i is the fraction of *edges* touching degree i variable nodes.
- For example, consider the Tanner graph:



  - 15 edges.
  - All are connected to degree-3 check nodes, so $\rho_3 = 15/15 = 1$.
  - Four are connected to degree-1 variable nodes, so $\lambda_1 = 4/15$.
  - Eight are connected to degree-2 variable nodes, so $\lambda_2 = 8/15$.
  - Three are connected to the degree-3 variable node, so $\lambda_3 = 3/15$.

Optimal Degree Distributions

- First, let's optimize for uniform 32-APSK.
  - The DVB-S2 standard rate $R_c = 3/5$ LDPC code has degree distributions:

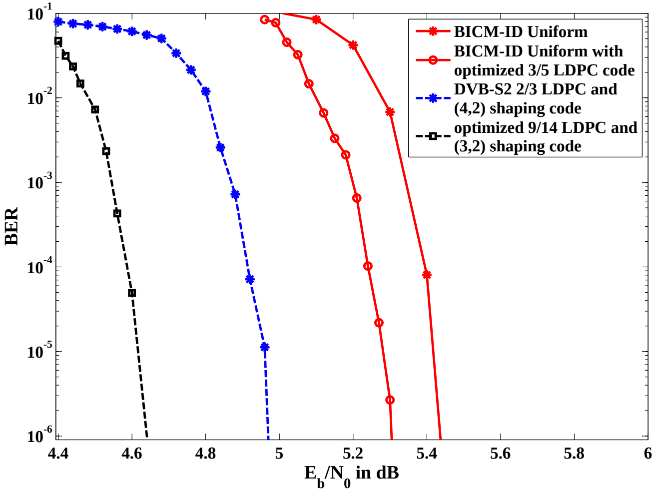
$$\begin{aligned} \rho_{11} &= 1 \\ \lambda_2 &= 0.182 \\ \lambda_3 &= 0.273 \\ \lambda_{12} &= 0.545 \end{aligned}$$

  - The optimized degree distributions are:

$$\begin{aligned} \rho_{11} &= 1 \\ \lambda_2 &= 0.182 \\ \lambda_4 &= 0.473 \\ \lambda_{19} &= 0.345 \end{aligned}$$

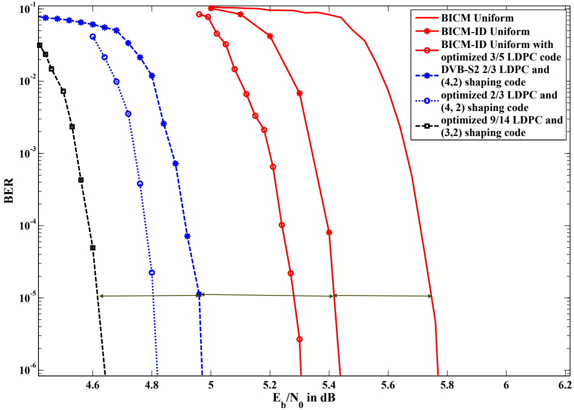
- A similar optimization can be performed for shaped 32-APSK.

BER with Optimized Degree Distributions



- BER of 32-APSK in AWGN at rate R=3 bits/symbol.
- Comparison of standard vs. optimized LDPC codes.

Summary of Performance Gains



- 0.33 dB gain from using BICM-ID.
- 0.46 dB gain from using shaping.
- 0.34 dB gain from optimizing LDPC code.
- Cumulative gain of 1.13 dB.

Outline

Conclusion

- DVB-S2 is a highly efficient system, thanks to
  - APSK modulation.
  - Tight RC-rolloff filtering.
  - Capacity-approaching irregular LDPC codes.
- The performance of DVB-S2 can be improved by
  - BICM-ID.
  - Constellation shaping.
  - Optimization of LDPC degree-distribution.
- The cumulative gain is 1 dB with all of these.
- Future work:
  - Application to 64APSK and other modulations.
  - Joint design of shaped modulation and code.

References

1 M.C. Valenti and X. Xiang, "Constellation shaping for bit-interleaved coded APSK," in *Proc. IEEE Int. Conf. on Commun. (ICC)*, (Kyoto, Japan), June 2011.

2 C. Nannapaneni, M.C. Valenti, and X. Xiang, "Constellation shaping for communication channels with quantized outputs," in *Proc. Conf. on Info. Sci. and Sys. (CISS)*, (Baltimore, MD), Mar. 2011.

3 X. Xiang and M.C. Valenti, "Improving DVB-S2 performance through constellation shaping and iterative demapping," in *Proc. IEEE Military Commun. Conf. (MILCOM)*, (Baltimore, MD), Nov. 2011.

4 X. Xiang and M.C. Valenti, "LDPC-coded APSK with constellation shaping and optimized degree distributions, " submitted to *IEEE Globecom*, (Anaheim, CA), Dec. 2012. In review.

5 M.C. Valenti and X. Xiang, "Constellation shaping for bit-interleaved LDPC coded APSK," submitted to *IEEE Trans. Commun.*, revision under review.

Thank You.