The BroadVoice® Speech Coding Algorithm

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Introduction

- BroadVoice16 (BV16):
  - 16 kb/s narrowband speech codec with 8 kHz sampling
  - Selected by CableLabs in 2004 as a standard codec in PacketCable 1.5 for Voice over Cable applications; later also became a standard codec in PacketCable 2.0
  - Standardized by SCTE and ANSI in 2006 as "ANSI/SCTE 24-21 2006" standard
  - One of the standard codecs listed in the ITU-T Recommendation J.161
- BroadVoice32 (BV32):
  - 32 kb/s wideband speech codec with 16 kHz sampling
  - Standard codecs in PacketCable 2.0, "ANSI/SCTE 24-23 2007", and ITU-T Recommendation J.361
- BV16 and BV32 are:
  - based on Two-Stage Noise Feedback Coding (TSNFC)
  - optimized for **low delay**, **low complexity**, and **high speech quality**
  - Royalty-free and open source (both floating-point and fixed-point C)
  - Visit http://www.broadcom.com/broadvoice for info & code download

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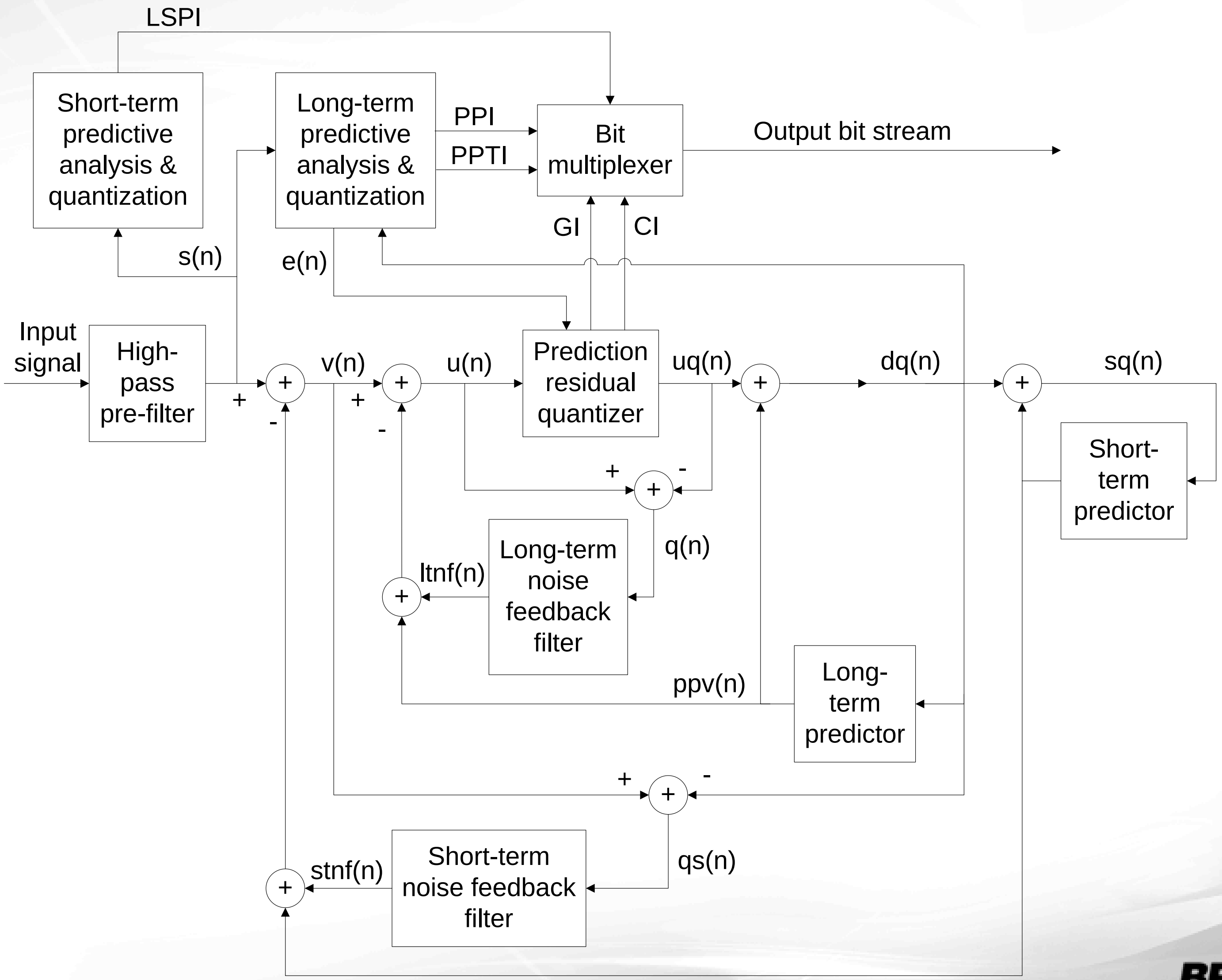
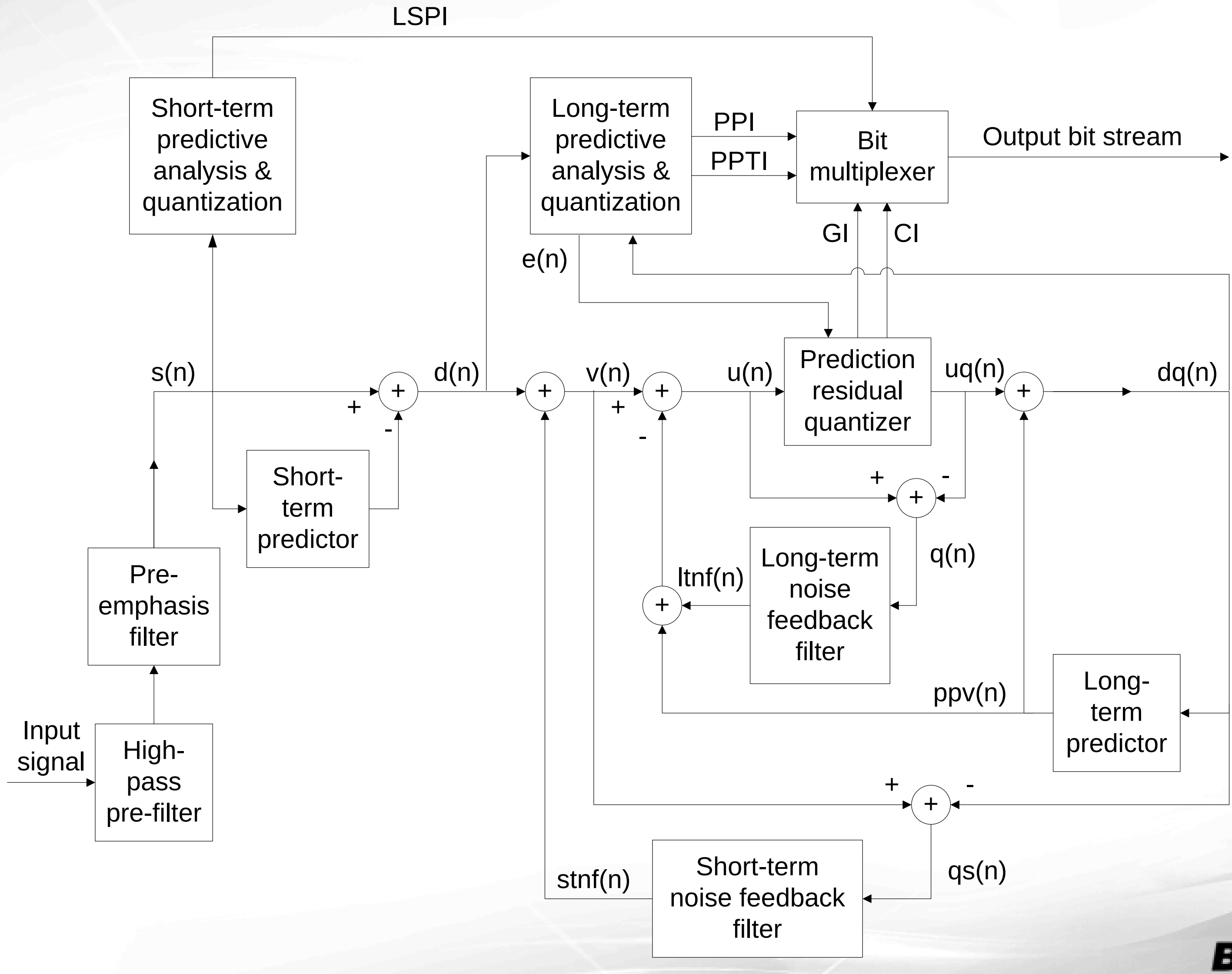
BV16 Encoder Structure



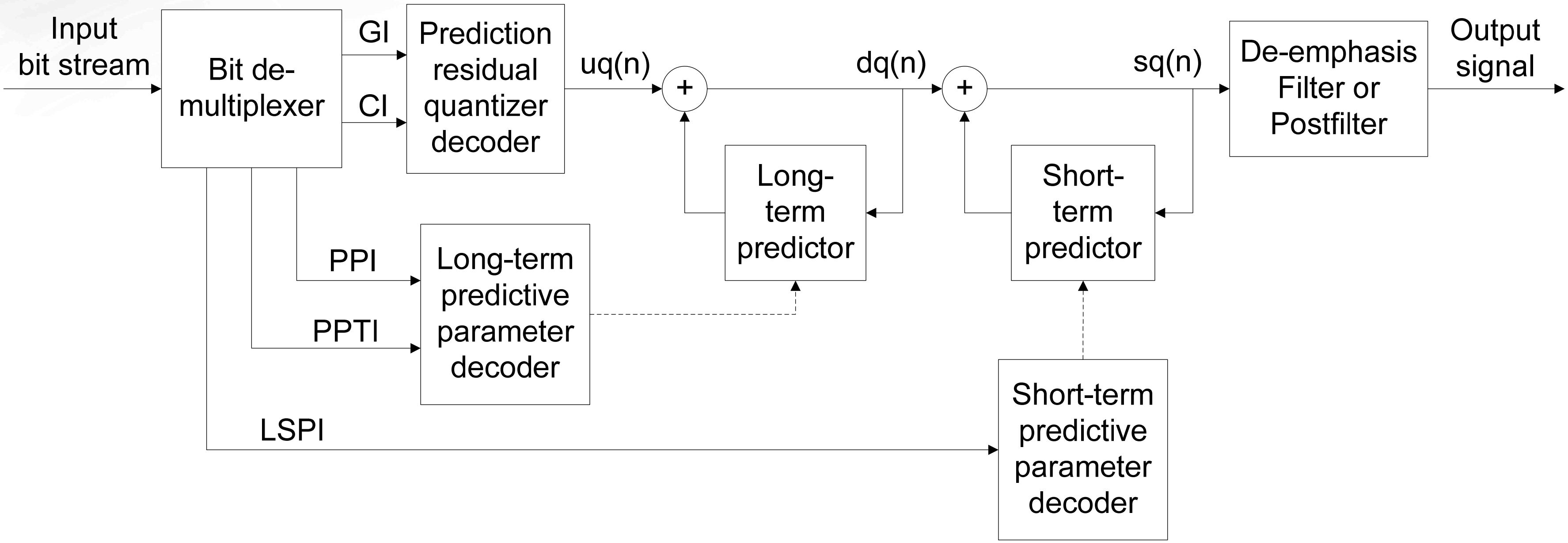
- BV16 uses TSNFC Form 3 structure in our ICASSP 2006 paper

BV32 Encoder Structure



- BV32 uses TSNFC Form 2 structure in our ICASSP 2006 paper

BV16/BV32 Decoder Structure



- Similar to a CELP decoder
- BV32 uses a de-emphasis filter but not a postfilter
- BV16 does not use a de-emphasis filter but may add a postfilter

Short-Term Prediction

- Use 8th-order short-term prediction to keep complexity low
- LSP quantized using 8th-order MA prediction and two-stage VQ:
  - 1st-stage: 8-dimensional VQ with 7-bit codebook
  - 2nd-stage: BV16 uses 8-dimensional VQ with 1-bit sign and 6-bit shape
    BV32 uses split VQ with 3-5 split and 5 bits each
- BroadVoice might be used in non-VoIP applications with bit errors
  - Desirable to make it robust to bit errors
- Only codevectors that preserve the order of first 3 LSPs are allowed in the 2nd-stage VQ codebook search
  - order reversal at decoder indicates bit errors → last LSP vector used
  - greatly reduces distortion due to bit errors without sending redundant information
  - essentially no degradation to clear-channel quality

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Short-Term Noise Spectral Shaping

- TSNFC Form 2 structure of BV32 has a lower complexity but gives a more constrained noise spectral shape of

$$N_{BV32}(z) = \frac{\tilde{A}(z/\gamma)}{\tilde{A}(z)}$$

- TSNFC Form 3 structure of BV16 has a higher complexity but gives a more general noise spectral shape of

$$N_{BV16}(z) = \frac{A(z/\gamma_1)}{A(z/\gamma_2)}$$

- $\tilde{A}(z)$ uses quantized coefficients while $A(z)$ uses unquantized ones

- $\gamma = 0.75$ for BV32; $\gamma_1 = 0.5$ and $\gamma_2 = 0.85$ for BV16

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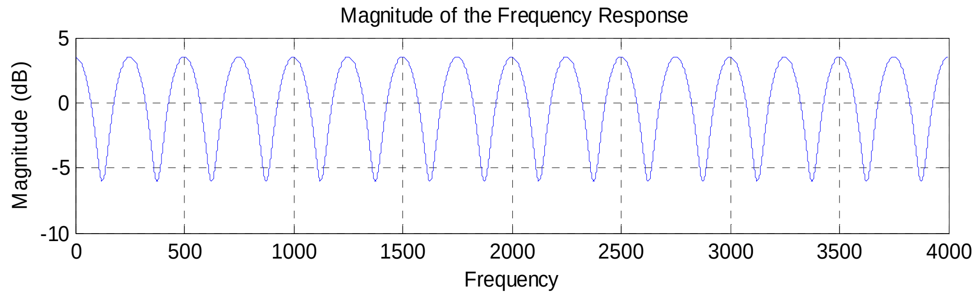
Long-Term Prediction and Noise Spectral Shaping

- Long-Term Prediction:
  - 3-tap pitch predictor with integer pitch period
  - pitch period encoded to 7 bits for BV16 and 8 bits for BV32
  - pitch period range: 10 to 136 for BV16 and 10 to 264 for BV32
  - 3 pitch predictor taps vector quantized to 5 bits
  - pitch period and pitch taps determined in open-loop fashion to save complexity
- Long-Term Noise Spectral Shaping:
  - To keep the complexity low, the noise feedback filter has a simple form of

$$F_l(z) = N_l(z) - 1 = \lambda z^{-pp}$$

  - λ is half of optimal single-tap pitch predictor coefficient, range-limited to [0, 1]
  - The corresponding noise spectral shape is given by $N_l(z) = 1 + \lambda z^{-pp}$
  - Example:



Gain Quantization

- Excitation gain derived and quantized in open-loop to save complexity
- 1 gain/frame for BV16, and 2 gains/frame for BV32
- Gain: base-2 logarithm of average power of open-loop prediction residual
- Fixed moving-average (MA) prediction of gain using 40 ms worth of previous data:
  - 8^{th}-order MA predictor for BV16
  - 16^{th}-order MA predictor for BV32
- Scalar quantization of MA prediction residual of log-gain:
  - 4 bits for BV16
  - 5 bits for BV32

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Gain Change Limitation

- Problem: Bit errors can cause large “gain pops” in decoded speech
- Solution: Limit the maximum gain increase allowed, conditioned on the previous log-gain and previous log-gain change
  - Train a “constraint threshold matrix” off-line:
    - Row: log-gain relative to a long-term average log-gain
    - Column: log-gain change between adjacent gains
    - Matrix element values: 99.x percentile of observed log-gain change in natural speech
  - In gain encoding, if quantized gain gives a log-gain change > threshold, reduce the quantized gain until < threshold, or until the smallest gain in gain codebook
  - In gain decoding, if the gain code is not for the smallest gain in gain codebook and the decoded gain gives a log-gain change > threshold, then the gain is corrupted by bit errors → replace with the last decoded gain value
- Result: All severe “gain pops” eliminated, no redundant bit needed, and clear-channel performance hardly affected

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Excitation Vector Quantization

- Excitation VQ dimension = 4
  - BV16: 1-bit sign, 4-bit shape, (1+4)/4 = 1.25 bits/sample
  - BV32: 1-bit sign, 5-bit shape, (1+5)/4 = 1.5 bits/sample
  - VQ codebook closed-loop trained
- Analysis-by-synthesis codebook search:
  - concept: pass all codevectors through TSNFC structure, pick the one that gives minimum energy of quantization error
- Efficient VQ codebook search:
  - treat TSNFC structure as a linear system with VQ codevector as input and quantization error vector as output
  - decompose quantization error vector into Zero-Input Response (ZIR) and Zero-State Response (ZSR) → see our ICASSP 2006 paper
  - further complexity reduction → see our Interspeech 2006 paper

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Bit Allocation

Parameter	BV16	BV32
LSP	7+7=14	7+(5+5)=17
Pitch period	7	8
3 pitch taps	5	5
Excitation gain(s)	4	5+5=10
Excitation vectors	(1+4)×10=50	(1+5)×20=120
Total per frame	80 bits/40 samples	160 bits/80 samples

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Postfiltering (PF) and Packet Loss Concealment (PLC)

- BV16 and BV32 are not bit-exact standards
- PF and PLC are both post-processing steps after decoding
- PF and PLC do not affect bit-stream compatibility
- PF and PLC are not really part of the BV16/BV32 standards
- BV16 specification gives an example PF
- BV16/BV32 specifications each gives an example PLC
- Other PF and PLC schemes can be used without affecting inter-operability with the BV16/BV32 standards

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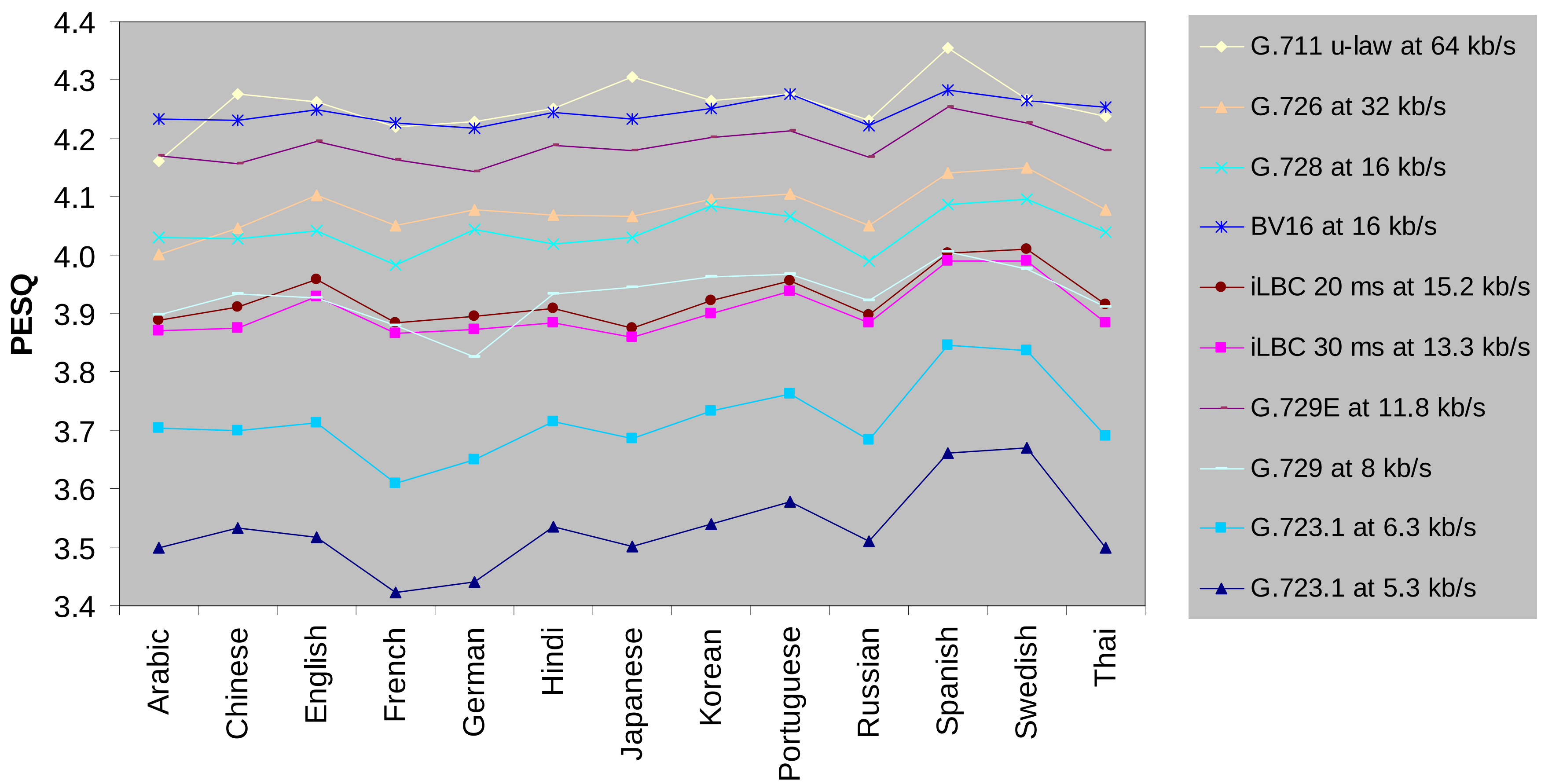
Complexity Comparison with Other CELP-Based Standard Codecs*

Codec	MIPS	RAM (kwords)	ROM (kwords)	Total Memory Footprint	Algorithmic Delay (ms)
G.728	36	2.2	6.7	9	0.625
G.729	22	2.6	14	17	15
G.729E	27	2.6	20	23	15
G.723.1	19	2.1	20	22	37.5
EVRC	25	2.5	?	?	30
AMR	20	4.6	17	22	25
BV16	12	2	11	13	5
G.722.2	40	5.3	18	23	26.875
VMR-WB	40	9.05	?	?	33.75
G.729.1	40	8.7	40.5	49	48.9375
BV32	17	3	10	13	5

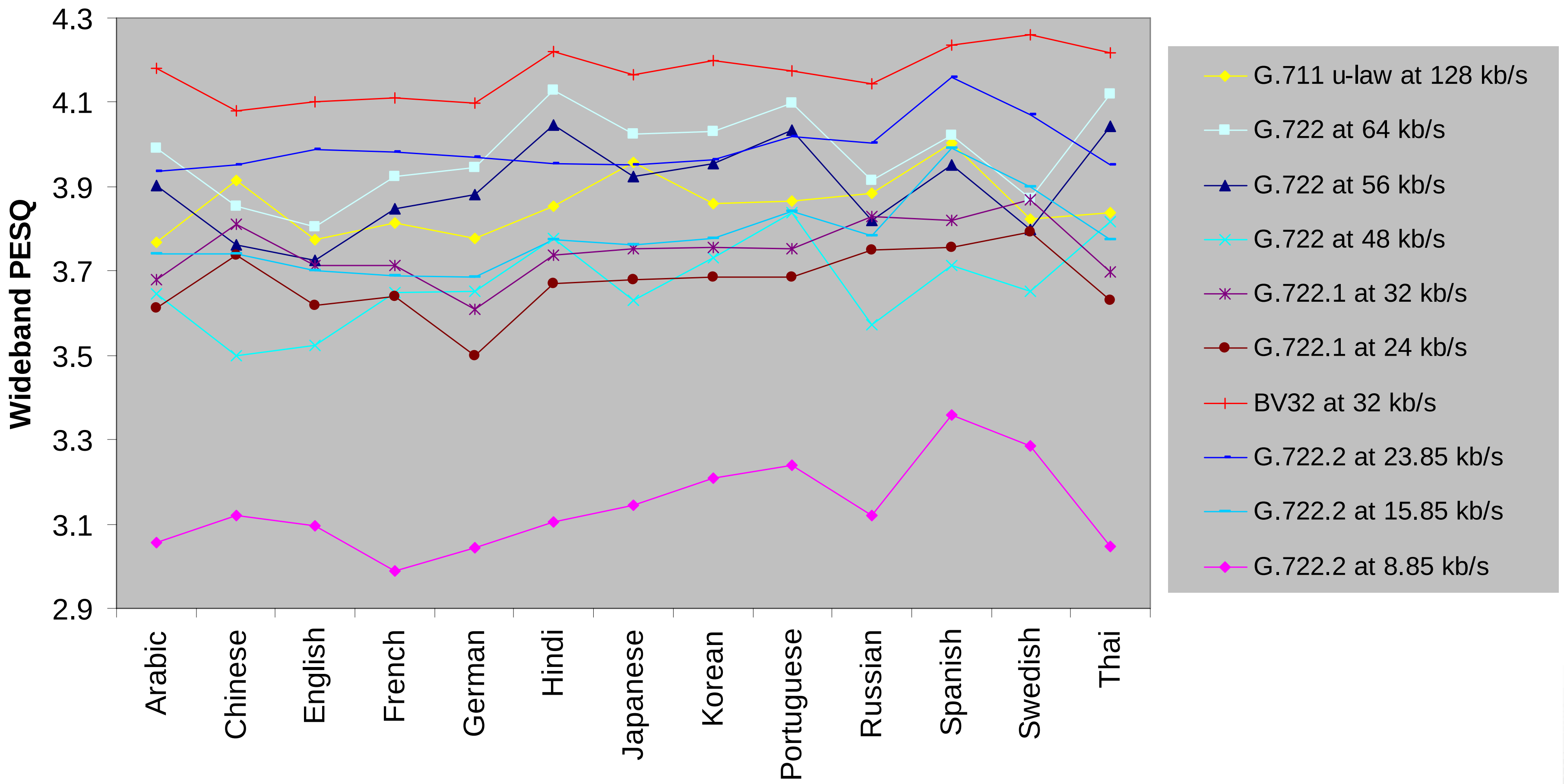
* Most data extracted from PacketCable 2.0 spec audio codec comparison table

Narrowband Speech Quality Measured by PESQ Using 13 Languages



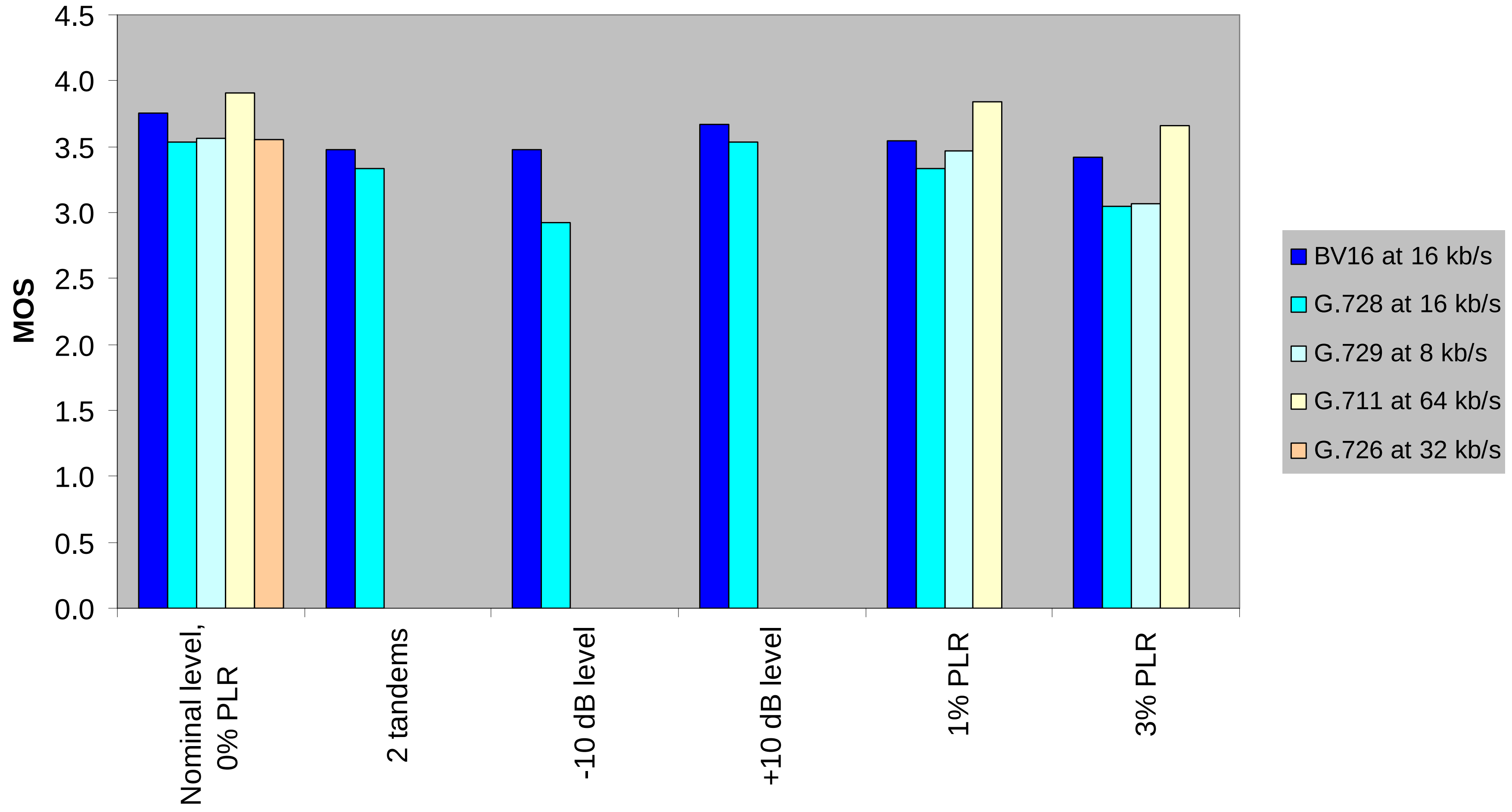
- All 96 sentence pairs of 13 languages in NTT 1994 database were used
- BV16 was rated higher than all other codecs here except 64 kb/s G.711

Wideband Speech Quality Measured by Wideband PESQ Using 13 Languages



- All 96 sentence pairs of 13 languages in NTT 1994 database were used
- BV32 was rated higher than all other codecs listed here

Narrowband Listening Test Results



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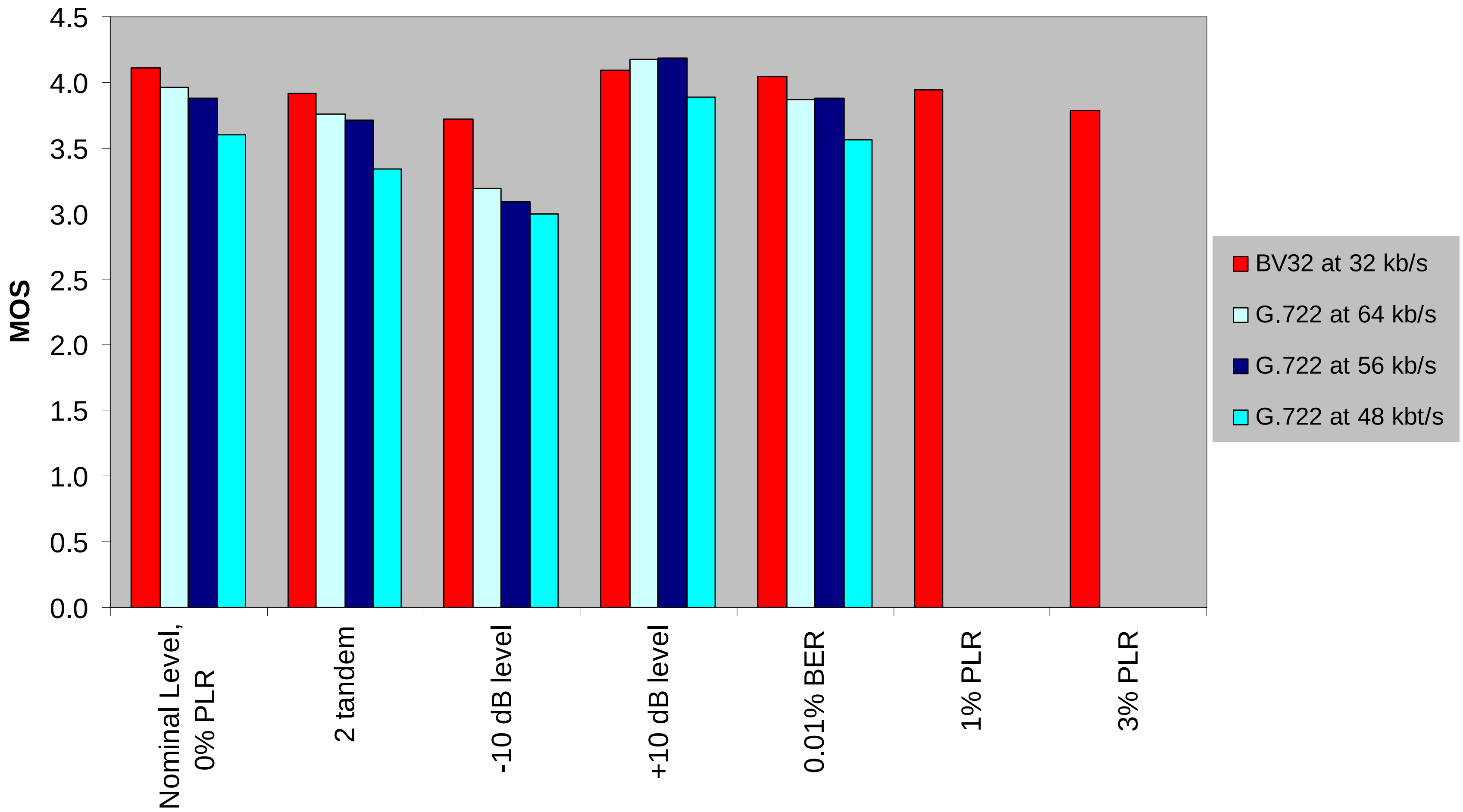
Wideband Listening Test Results



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BroadVoice Subjective Speech Quality Relative to Reference Codecs

- Dynastat did narrowband MOS test; Comsat Labs did wideband test
- 32 naïve listeners in each test
- BV16 rated statistically better than G.728, G.729, and G.726 at 32 kb/s
- BV32 rated statistically better than G.722 at 64 kb/s
- BV16/BV32 give 0.5 MOS degradation at about 5% random packet loss, versus 2% to 3% for most other standard speech codecs

Narrowband Codec	MOS	Wideband Codec	MOS
G.711 μ-law	3.91	BV32	4.11
BV16	3.76	G.722 at 64 kb/s	3.96
G.729	3.56	G.722 at 56 kb/s	3.88
G.726 at 32 kb/s	3.56	G.722 at 48 kb/s	3.60
G.728	3.54		

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Conclusion

- BroadVoice16 and BroadVoice32 are based on novel Two-Stage Noise Feedback Coding with following design emphases:
  - Low delay: 3x to 8X lower algorithmic delay than most competing codecs
  - Low complexity: 2X to 3X lower MIPS, 1.3X to 3.8X lower memory footprint
  - High speech quality:
    - BV16 statistically better than toll-quality codecs G.726 at 32 kb/s, G.728, G.729
    - BV32 statistically better than G.722 at 64 kb/s
    - Slower degradation with increasing packet loss rate than most other codecs
- BV16 and BV32 are standard speech codecs of PacketCable 1.5/2.0, ANSI, SCTE, and ITU-T J.161/J.361 for VoIP over Cable applications
- BV16 and BV32 are royalty-free and open source
- BV16 and BV32 can potentially be a base layer codec of IETF Internet Interactive Audio Codec → benefit: can make IIAC inter-operable with existing ANSI/SCTE BV16/BV32 standards

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