3GPP TSG-RAN WG1 #47bis **R1-070464**
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Agenda Item: **6.4**
Document for: **Discussion and Decision**

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1. Introduction

It has been re-affirmed in TSG RAN WG1 #47 to replace the Rel6 turbo coding internal interleaver with a modern contention-free interleaver for lower hardware implementation costs and better support of high data rates. In accordance with the proposed way forward for selecting a final interleaver from the variety of candidates [1], this document provides a performance comparison of all proposals:

- Quadratic permutation polynomial (QPP) interleavers
    - Ericsson designs (QPP-E) [2]
    - Motorola designs (QPP-M) [3]
    - Qualcomm byte-aligned designs (QPP-Q) [4]
- Almost regular permutation (ARP) interleavers
    - Broadcom designs (ARP-B) [5]
    - Motorola designs (ARP-M) [3]
- Quasi-cyclic (QC) interleavers from France Telecomm. [6]
- Inter-block permutation (IBP) interleavers from ITRI [7]
- LRI interleavers from Mitsubishi Electric Corp. [8]

2. Performance Comparison Setup

All interleavers are applied to a turbo encoder with Rel6-type trellis termination as illustrated Fig. 4 of 3GPP TS 25.212 [9]. That is, for an input block of K bits, the coded output contains ($3K$+12) bits.

Since the 42 test block sizes [11] rarely correspond to the native lengths of the interleavers, two accommodating approaches are used.

- For contention-free interleaver candidates, code shortening [12, 13] is adopted.
    - For QPP and ARP interleavers, pre-padding is used.

      For interleaver size $S>K$, a block of ($S-K$) zeros are pre-pended to the input bits before encoding. After encoding, the systematic, 1st parity, and 2nd parity bits corresponding to these padding positions are punctured. The number of output bits is exactly ($3K$+12).
    - For IBP interleavers, distributed padding as specified in [7] is used.
- For the LRI interleaver proposal, address pruning as specified in [8] is used.
- For the reference prunable prime interleaver (PIL),[1] address pruning per 3GPP TS 25.212 is used.

The coded bits are assumed to be carried by the QPSK modulation over an additive white Gaussian noise (AWGN) channel. The received values are decoded by an improved Max-Log-MAP turbo decoder as illustrated in Figure 1.[2] Block error rates (BLER) are measured after 8 iterations. In order to extract reliable readings of required SNR values at various BLER targets, raw BLER results from simulations are interpolated as follows. All BLER points below 0.9 are first converted to the logarithmic domain and then fitted by a polynomial of the corresponding SNR points. The order of the fitting polynomial is set to `min(7,DataLength-3)`. Detailed plots of the raw and interpolated BLERs are provided in the Appendix A.

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[1] For K>5114, the Rel6 PIL specifications [9] are expanded with Rel-99 parameters [10].

[2] The improved Max-Log-MAP decoder provides SNR gains of 0.2—0.3 dB over the conventional Max-Log-MAP decoder with essentially no additional complexity.

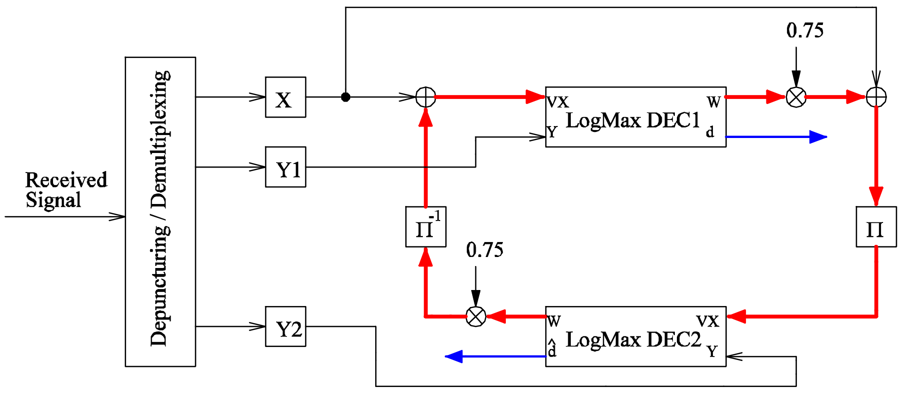

Figure 1 Illustration of an improved Max-Log-MAP turbo decoder.

3. Performance Comparison

The required SNR for four BLER targets (10%, 1%, 0.1% and 0.01%) are chosen as comparison points as agreed in the proposed way forward [1]. In the following four sections, the required E_b/N_0 values (in dB) for the reference PIL cases are first listed. The SNR differences of the interleaver proposals than the reference cases are then tabulated. With this convention, a negative SNR difference means a performance gain over the reference case. As an overall summary, the mean and standard deviation (STD) in SNR differences are computed for each interleaver proposals. Pair-wise comparisons between the proposals are provided in Appendix B.

3.1. SNR for BLER=10%

Test block length	E_b/N_0	E_b/N_0 difference than the reference							
	PIL Ref	QPP-E	QPP-M	QPP-Q	ARP-M	ARP-B	IBP	QC	LRI
40	1.547	−0.027	−0.050	−0.064	−0.036	0.027	−0.045	−0.063	−0.000
52	1.471	−0.046	−0.009	0.134	0.008	−0.081	−0.062	−0.014	−0.015
67	1.362	−0.045	−0.022	−0.007	−0.047	1.053	−0.058	−0.003	−0.011
87	1.274	−0.041	−0.041	−0.041	−0.058	0.015	−0.042	−0.020	−0.034
99	1.220	−0.040	−0.048	−0.040	−0.065	−0.032	−0.042	0.695	−0.036
113	1.167	−0.021	−0.019	−0.021	−0.040	−0.033	−0.059	−0.031	−0.013
129	1.112	−0.041	−0.024	−0.025	−0.031	0.029	−0.054	−0.005	−0.025
146	1.071	−0.027	−0.029	−0.019	−0.011	0.042	−0.037	−0.021	−0.020
167	1.014	−0.023	−0.010	−0.013	−0.015	0.005	−0.030	0.116	−0.003
190	0.971	−0.021	−0.011	−0.005	−0.005	0.002	0.000	−0.009	−0.005
216	0.913	0.018	0.007	0.034	0.002	0.032	0.040	0.000	0.019
246	0.886	−0.008	−0.018	0.005	−0.009	0.031	−0.002	0.101	−0.002
280	0.845	−0.008	−0.008	0.018	−0.002	0.011	0.016	0.005	0.015
319	0.817	−0.010	−0.007	0.010	−0.001	−0.005	−0.004	−0.003	−0.005
363	0.775	0.016	0.011	0.010	0.002	0.030	0.009	0.468	0.020
384	0.777	−0.008	−0.021	0.008	−0.010	0.051	−0.001	0.044	−0.002
414	0.734	−0.005	0.006	0.043	0.013	0.084	0.015	0.027	0.018
471	0.713	0.004	0.002	0.052	−0.003	0.073	0.004	0.610	0.004
536	0.676	0.004	0.015	0.050	0.008	0.163	0.027	0.025	0.023
611	0.654	0.019	0.010	0.014	0.005	0.022	0.010	0.034	0.019
695	0.632	0.015	0.016	0.078	0.003	0.027	0.010	0.034	0.025
792	0.621	0.009	0.007	0.006	0.005	0.073	0.020	0.050	0.027
902	0.590	0.012	0.004	0.089	0.010	0.009	0.010	0.061	0.034
1027	0.579	0.011	0.010	0.095	−0.003	0.051	0.000	0.034	0.012

1169	0.563	−0.003	0.011	0.281	0.001	0.061	0.000	0.087	0.005
1331	0.536	0.009	0.013	0.156	0.012	0.016	0.016	0.089	0.022
1536	0.529	0.005	−0.002	−0.001	−0.004	−0.003	−0.000	0.071	0.008
1725	0.512	0.001	−0.000	0.005	0.007	0.012	0.009	0.179	0.009
1965	0.503	0.009	0.031	0.056	−0.005	0.005	0.008	0.107	0.013
2237	0.489	0.003	0.034	0.036	0.003	0.016	0.005	0.344	0.011
2304	0.493	−0.002	−0.004	−0.007	−0.004	−0.006	−0.007	0.159	−0.002
2547	0.482	−0.013	−0.006	0.223	−0.001	0.027	−0.001	0.183	0.008
2900	0.470	−0.000	0.002	−0.002	−0.004	0.019	−0.001	0.208	0.006
3302	0.464	0.003	0.003	0.049	−0.001	0.003	−0.004	0.243	0.003
3760	0.458	−0.008	−0.009	0.127	−0.006	0.013	0.000	0.227	−0.003
4096	0.451	−0.001	−0.006	0.003	0.005	−0.005	0.000	0.316	−0.002
4281	0.443	−0.001	0.012	0.002	0.007	0.007	−0.003	0.317	−0.001
4874	0.443	−0.004	0.026	0.163	0.000	0.018	−0.003	0.404	−0.002
5550	0.433	0.003	−0.001	0.187	0.005	−0.000	0.003	0.407	0.000
6144	0.424	0.003	0.001	0.003	0.001	0.003	0.002	0.407	0.005
7195	0.421	0.018	0.010	−0.002	0.003	0.007	−0.006	0.517	0.004
8192	0.412	−0.003	0.000	0.004	0.009	−0.005	0.005	0.490	0.009
Mean		−0.006	−0.003	0.040	−0.006	0.045	−0.006	0.164	0.003
STD		0.018	0.019	0.075	0.018	0.164	0.024	0.197	0.015

3.2. SNR for BLER=1%

Test block length	E_b/N_0	E_b/N_0 difference than the reference							
	PIL Ref	QPP-E	QPP-M	QPP-Q	ARP-M	ARP-B	IBP	QC	LRI
40	2.675	−0.056	−0.050	−0.058	−0.007	0.111	−0.050	−0.064	0.022
52	2.461	−0.042	0.021	0.383	0.052	−0.085	−0.048	−0.016	0.023
67	2.263	−0.052	−0.011	−0.000	−0.065	1.454	−0.080	0.002	0.009
87	2.078	−0.042	−0.042	−0.042	−0.078	0.067	−0.062	−0.002	−0.016
99	1.965	−0.030	−0.037	−0.030	−0.036	−0.035	−0.050	1.442	−0.010
113	1.882	−0.029	−0.047	−0.029	−0.036	−0.051	−0.055	−0.034	−0.016
129	1.803	−0.057	−0.057	−0.030	−0.053	0.067	−0.072	−0.013	−0.018
146	1.723	−0.052	−0.042	−0.032	−0.027	0.068	−0.068	−0.043	−0.019
167	1.596	−0.017	0.006	0.000	−0.016	0.099	−0.001	0.484	0.002
190	1.533	−0.030	−0.002	−0.018	−0.027	−0.001	−0.003	−0.022	−0.025
216	1.440	−0.011	−0.005	0.033	−0.001	0.036	0.049	0.004	0.017
246	1.371	−0.015	−0.007	0.021	0.006	0.077	0.009	0.187	0.021
280	1.305	−0.008	−0.007	0.040	−0.007	0.005	0.010	−0.001	0.011
319	1.242	−0.007	−0.007	0.031	0.012	0.011	0.009	0.008	0.021
363	1.189	0.008	0.009	0.007	−0.009	0.040	−0.000	1.205	0.004
384	1.172	−0.010	−0.015	0.020	−0.006	0.089	0.009	0.094	−0.006
414	1.120	−0.002	0.002	0.065	−0.005	0.119	0.002	0.039	0.019
471	1.080	0.008	−0.002	0.067	−0.014	0.104	−0.005	1.449	0.001
536	1.026	−0.007	−0.002	0.054	−0.001	0.728	0.001	0.034	0.007
611	0.969	0.007	0.002	0.016	0.005	0.034	0.011	0.154	0.029

695	0.941	0.006	−0.008	0.105	−0.006	0.005	−0.007	0.162	0.013
792	0.897	0.005	−0.004	0.008	0.003	0.094	0.032	0.117	0.030
902	0.863	−0.011	−0.008	0.155	−0.003	−0.009	−0.007	0.127	0.021
1027	0.826	−0.001	0.006	0.194	−0.012	0.062	−0.010	0.135	0.007
1169	0.790	0.001	0.012	0.434	−0.001	0.079	0.002	0.393	0.018
1331	0.768	−0.011	−0.004	0.263	−0.008	−0.004	−0.000	0.286	0.004
1536	0.727	0.001	−0.003	0.003	−0.006	−0.002	−0.000	0.279	0.014
1725	0.705	−0.002	−0.007	0.000	−0.003	0.013	0.001	0.558	0.007
1965	0.680	0.003	0.031	0.106	−0.005	−0.002	0.005	0.392	0.011
2237	0.658	−0.006	0.041	0.041	−0.004	0.008	0.002	0.632	0.003
2304	0.654	−0.010	−0.002	−0.004	−0.001	0.004	−0.006	0.530	0.006
2547	0.641	−0.006	−0.004	0.359	−0.003	0.032	−0.011	0.621	0.015
2900	0.618	−0.002	−0.006	−0.005	−0.010	0.019	−0.001	0.706	0.001
3302	0.596	0.006	0.006	0.150	0.003	0.006	0.003	0.778	0.004
3760	0.578	−0.000	0.006	0.244	0.008	0.010	0.002	0.789	0.007
4096	0.569	−0.001	0.003	0.010	0.013	0.004	0.002	0.877	0.010
4281	0.565	0.001	0.017	−0.005	0.005	−0.002	−0.003	0.922	−0.003
4874	0.548	0.003	0.039	0.298	0.011	0.027	−0.001	0.974	0.006
5550	0.534	0.009	0.004	0.343	0.006	0.005	0.008	1.024	0.001
6144	0.519	0.005	0.004	0.002	0.007	0.007	0.000	1.070	0.010
7195	0.511	0.021	0.013	−0.001	0.004	0.009	−0.001	1.152	0.002
8192	0.498	−0.000	0.001	0.005	0.013	0.002	0.003	1.178	0.011
Mean		−0.010	−0.004	0.076	−0.007	0.079	−0.009	0.443	0.007
STD		0.020	0.021	0.130	0.022	0.247	0.028	0.464	0.013

3.3. SNR for BLER=0.1%

Test block length	E_b/N_0	E_b/N_0 difference than the reference							
	PIL Ref	QPP-E	QPP-M	QPP-Q	ARP-M	ARP-B	IBP	QC	LRI
40	3.525	−0.110	−0.124	−0.111	−0.084	0.275	−0.096	−0.124	0.001
52	3.237	−0.099	0.009	0.706	0.053	−0.164	−0.126	−0.036	0.000
67	2.941	−0.084	0.017	0.005	−0.103	1.804	−0.119	−0.002	−0.002
87	2.692	−0.091	−0.091	−0.091	−0.138	0.110	−0.074	0.001	−0.051
99	2.558	−0.080	−0.065	−0.080	−0.074	−0.080	−0.106	2.090	−0.055
113	2.434	−0.074	−0.084	−0.074	−0.073	−0.097	−0.105	−0.058	−0.046
129	2.362	−0.114	−0.105	−0.065	−0.118	0.118	−0.141	−0.058	−0.078
146	2.230	−0.087	−0.077	−0.075	−0.059	0.086	−0.111	−0.090	−0.065
167	2.047	−0.052	−0.011	0.004	−0.038	0.436	0.003	1.081	−0.015
190	1.954	−0.054	−0.009	−0.018	−0.047	−0.022	−0.016	−0.040	−0.022
216	1.829	−0.032	−0.024	0.066	−0.015	0.069	0.061	0.002	0.013
246	1.743	−0.027	−0.021	0.036	−0.007	0.114	0.002	0.386	0.023
280	1.659	−0.017	−0.003	0.073	−0.023	−0.006	0.010	−0.015	0.046
319	1.546	0.009	0.002	0.084	0.044	0.027	0.017	0.035	0.039
363	1.500	−0.000	0.004	0.013	−0.032	0.108	0.003	1.915	0.008
384	1.475	−0.035	−0.034	0.075	−0.011	0.157	0.014	0.233	−0.015

414	1.427	−0.036	−0.032	0.146	−0.031	0.169	−0.022	0.059	0.011
471	1.342	0.013	0.015	0.196	−0.005	0.184	−0.001	2.200	0.027
536	1.303	−0.038	−0.039	0.077	−0.030	1.663	−0.020	0.112	−0.010
611	1.220	−0.004	−0.012	0.023	−0.007	0.014	0.013	0.604	0.052
695	1.168	−0.007	−0.016	0.251	−0.014	0.003	−0.009	0.671	0.015
792	1.113	−0.014	−0.024	−0.009	−0.009	0.169	0.039	0.310	0.030
902	1.059	−0.017	−0.006	0.381	−0.005	−0.012	−0.010	0.387	0.063
1027	1.004	−0.002	0.019	0.467	−0.004	0.125	0.003	0.592	0.023
1169	0.963	−0.004	0.016	0.708	−0.002	0.139	0.013	1.074	0.030
1331	0.923	−0.003	0.003	0.599	−0.008	0.054	0.002	0.881	0.030
1536	0.888	−0.013	−0.015	−0.010	−0.022	−0.018	−0.014	0.855	0.004
1725	0.849	−0.007	−0.006	0.009	−0.005	0.015	−0.004	1.113	0.011
1965	0.818	−0.012	0.028	0.315	−0.007	−0.015	−0.004	1.005	0.015
2237	0.792	−0.020	0.043	0.044	−0.020	0.002	−0.010	1.151	−0.005
2304	0.778	−0.014	−0.004	−0.004	−0.007	0.004	0.007	1.176	0.007
2547	0.763	−0.017	−0.014	0.692	−0.010	0.044	−0.009	1.250	0.014
2900	0.736	−0.013	−0.006	−0.007	−0.011	0.022	0.004	1.298	−0.000
3302	0.709	−0.004	−0.004	0.567	−0.006	0.003	−0.005	1.358	0.002
3760	0.687	−0.014	−0.009	0.614	0.001	0.008	−0.012	1.348	−0.006
4096	0.679	−0.019	−0.015	0.001	−0.006	−0.008	−0.015	1.461	0.000
4281	0.664	−0.008	0.013	−0.015	−0.000	−0.001	−0.006	1.506	−0.003
4874	0.640	−0.001	0.042	0.710	0.007	0.045	−0.000	1.541	0.001
5550	0.628	−0.006	−0.009	0.727	−0.003	−0.008	−0.003	1.586	−0.004
6144	0.613	−0.013	−0.004	−0.008	−0.007	−0.007	−0.012	1.636	0.010
7195	0.600	0.005	0.007	−0.019	−0.006	0.005	−0.015	1.693	−0.009
8192	0.589	−0.019	−0.020	−0.017	−0.001	−0.013	−0.022	1.754	−0.008
Mean		−0.029	−0.016	0.166	−0.022	0.131	−0.021	0.808	0.002
STD		0.034	0.036	0.274	0.038	0.377	0.047	0.711	0.029

3.4. SNR for BLER=0.01%

Test block length	E_b/N_0	E_b/N_0 difference than the reference							
	PIL Ref	QPP-E	QPP-M	QPP-Q	ARP-M	ARP-B	IBP	QC	LRI
40	4.258	−0.161	−0.167	−0.173	−0.161	0.555	−0.158	−0.186	0.021
52	3.937	−0.191	0.013	0.994	0.053	−0.293	−0.206	−0.123	0.018
67	3.614	−0.208	0.042	0.017	−0.215	2.005	−0.233	−0.046	−0.042
87	3.312	−0.186	−0.186	−0.186	−0.237	0.159	−0.156	0.028	−0.151
99	3.163	−0.198	−0.195	−0.198	−0.200	−0.210	−0.207	2.551	−0.160
113	2.967	−0.104	−0.127	−0.104	−0.135	−0.152	−0.213	−0.111	−0.037
129	2.940	−0.200	−0.198	−0.165	−0.264	0.229	−0.249	−0.122	−0.216
146	2.811	−0.190	−0.201	−0.192	−0.138	0.044	−0.283	−0.256	−0.188
167	2.541	−0.167	−0.095	−0.077	−0.119	0.981	−0.031	1.530	−0.100
190	2.395	−0.154	−0.064	−0.007	−0.095	−0.054	−0.092	−0.061	−0.044
216	2.219	−0.074	−0.071	0.180	−0.056	0.149	0.042	0.009	−0.017
246	2.107	−0.045	−0.082	0.079	−0.037	0.148	−0.042	0.663	0.011

280	2.005	−0.061	0.097	0.218	−0.073	−0.011	−0.001	−0.005	0.266
319	1.858	−0.009	−0.021	0.241	0.046	0.032	−0.010	0.063	0.045
363	1.787	−0.013	−0.015	0.030	−0.049	0.376	0.100	2.450	0.100
384	1.792	−0.100	−0.113	0.296	−0.074	0.235	−0.011	0.487	−0.033
414	1.695	−0.057	−0.072	0.624	−0.046	0.292	−0.011	0.247	0.032
471	1.588	0.028	0.055	0.469	−0.009	0.344	0.006	2.778	0.080
536	1.548	−0.076	−0.058	0.261	−0.055	2.338	−0.021	0.471	0.007
611	1.505	−0.041	−0.068	0.013	−0.065	−0.047	−0.019	1.067	0.166
695	1.391	−0.024	−0.031	0.685	−0.034	0.005	−0.011	1.186	0.040
792	1.331	−0.059	−0.060	−0.047	−0.022	0.280	0.076	0.782	0.071
902	1.246	−0.003	0.009	0.910	0.020	−0.002	−0.014	0.854	0.344
1027	1.204	−0.032	0.012	0.949	−0.041	0.227	−0.025	1.073	0.051
1169	1.152	−0.045	0.021	1.002	−0.057	0.281	0.063	1.625	0.034
1331	1.091	−0.033	−0.009	1.059	−0.032	0.352	−0.021	1.338	0.035
1536	1.082	−0.071	−0.058	−0.066	−0.082	−0.085	−0.058	1.307	−0.018
1725	1.019	−0.060	−0.055	0.032	−0.037	−0.011	−0.034	1.587	−0.019
1965	0.996	−0.061	−0.032	0.810	−0.072	−0.064	−0.055	1.508	0.036
2237	1.005	−0.119	−0.040	−0.034	−0.124	−0.082	−0.103	1.503	−0.054
2304	0.922	−0.035	−0.045	−0.031	−0.034	−0.033	0.002	1.641	−0.018
2547	0.927	−0.076	−0.077	1.038	−0.074	0.054	−0.071	1.660	−0.017
2900	0.854	−0.035	−0.018	0.007	−0.036	0.048	0.002	1.781	−0.016
3302	0.859	−0.061	−0.061	0.918	−0.055	−0.049	−0.037	1.833	−0.039
3760	0.877	−0.116	−0.102	0.995	−0.089	0.170	−0.105	1.804	−0.098
4096	0.933	−0.184	−0.187	−0.116	−0.183	−0.169	−0.183	1.831	−0.120
4281	0.791	−0.056	−0.029	−0.060	−0.034	0.188	−0.019	1.990	−0.009
4874	0.780	−0.050	−0.006	1.164	−0.047	0.232	−0.008	2.034	−0.051
5550	0.902	−0.207	−0.208	1.070	−0.181	−0.206	−0.192	1.934	−0.145
6144	0.810	−0.135	−0.098	−0.106	−0.130	−0.127	−0.113	2.038	−0.047
7195	0.759	−0.083	−0.048	−0.109	−0.074	−0.032	−0.105	2.175	−0.075
8192	0.887	−0.241	−0.244	−0.244	−0.210	−0.243	−0.252	2.010	−0.226
Mean		−0.095	−0.069	0.289	−0.085	0.187	−0.073	1.117	−0.014
STD		0.069	0.078	0.470	0.073	0.508	0.097	0.895	0.111

4. Conclusion

Contention-free QPP interleavers provide consistent performance and hardware implementation [14] advantages over contention-making interleavers.

5. References

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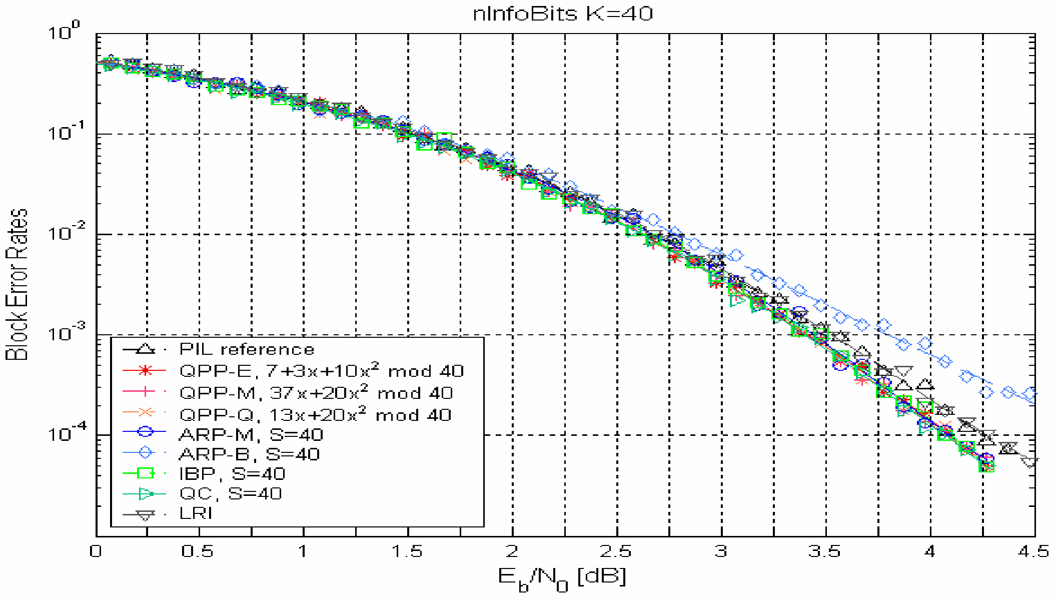
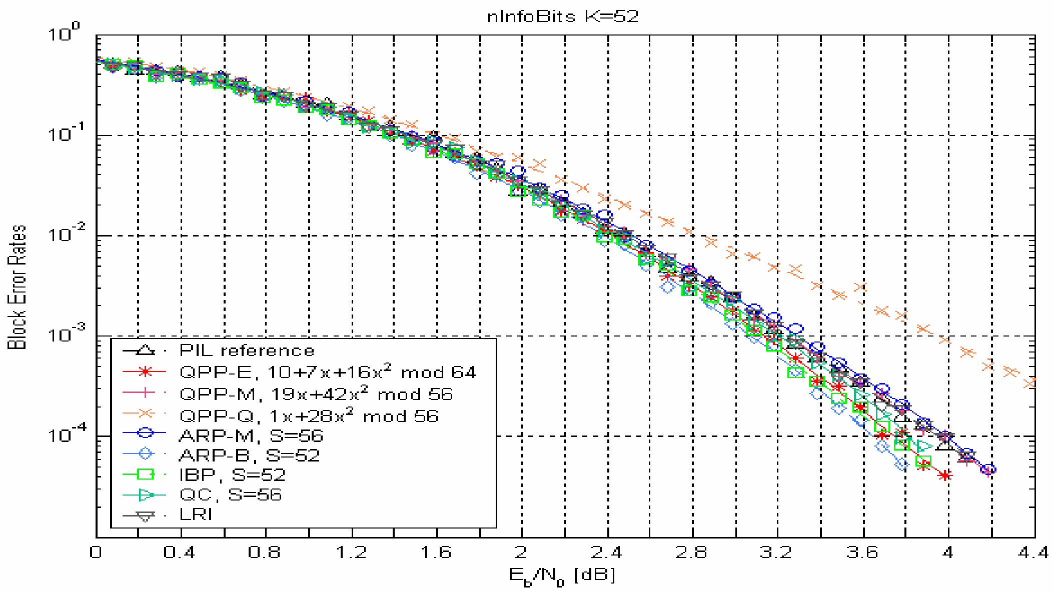
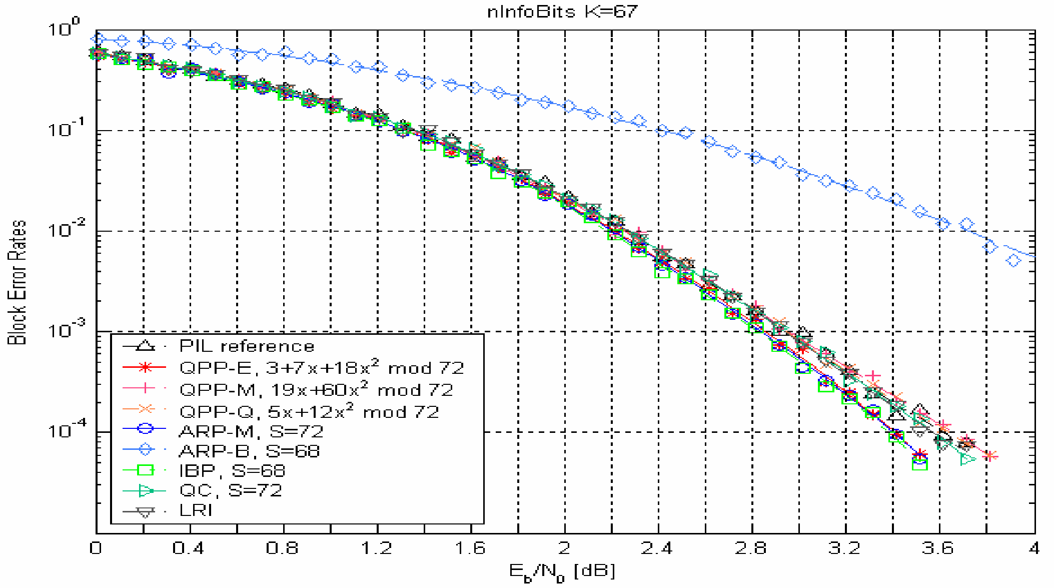
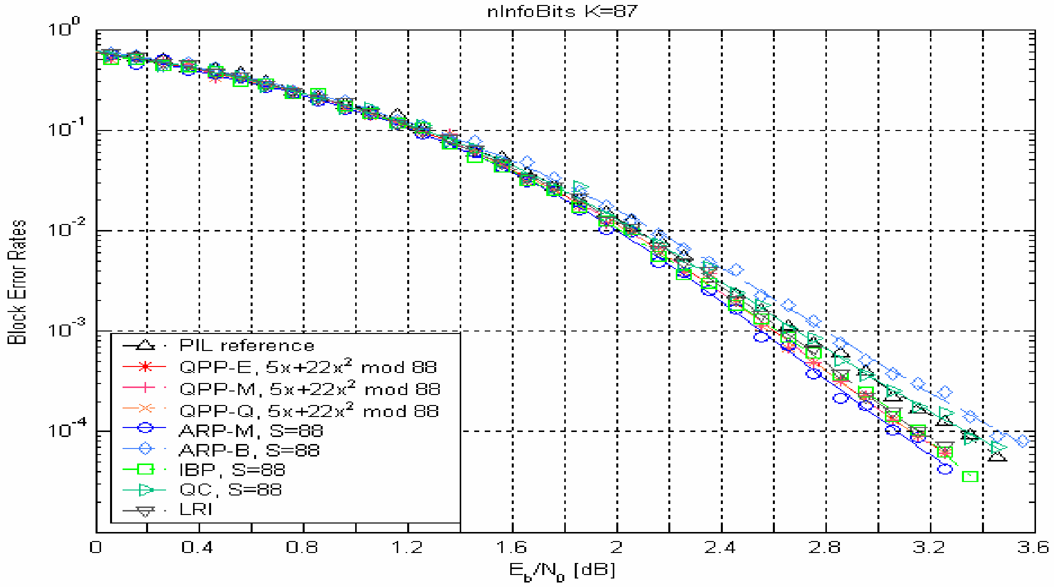
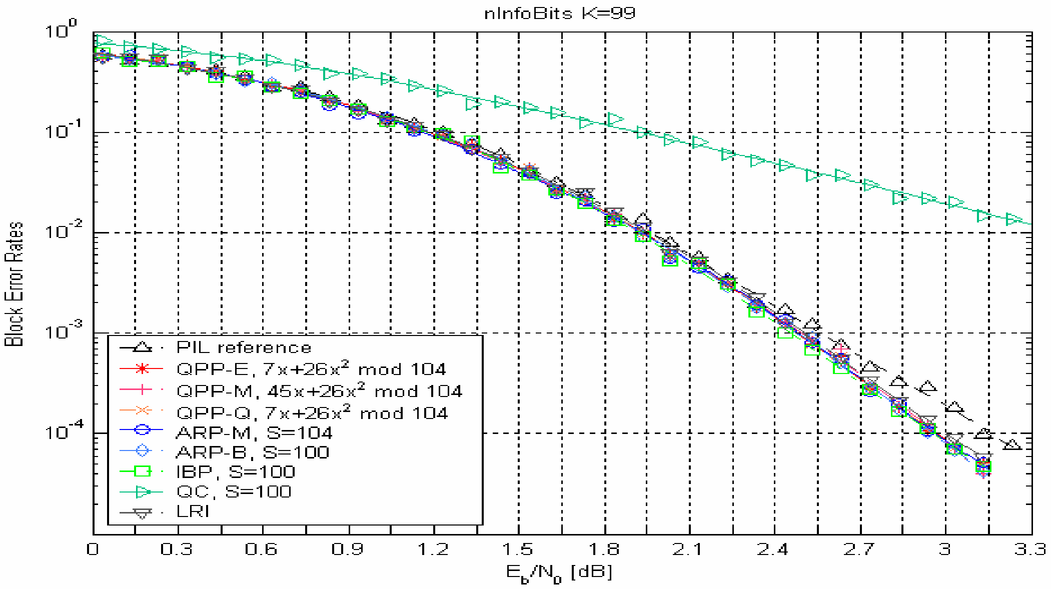
Appendix A — Detailed Plots of All Results

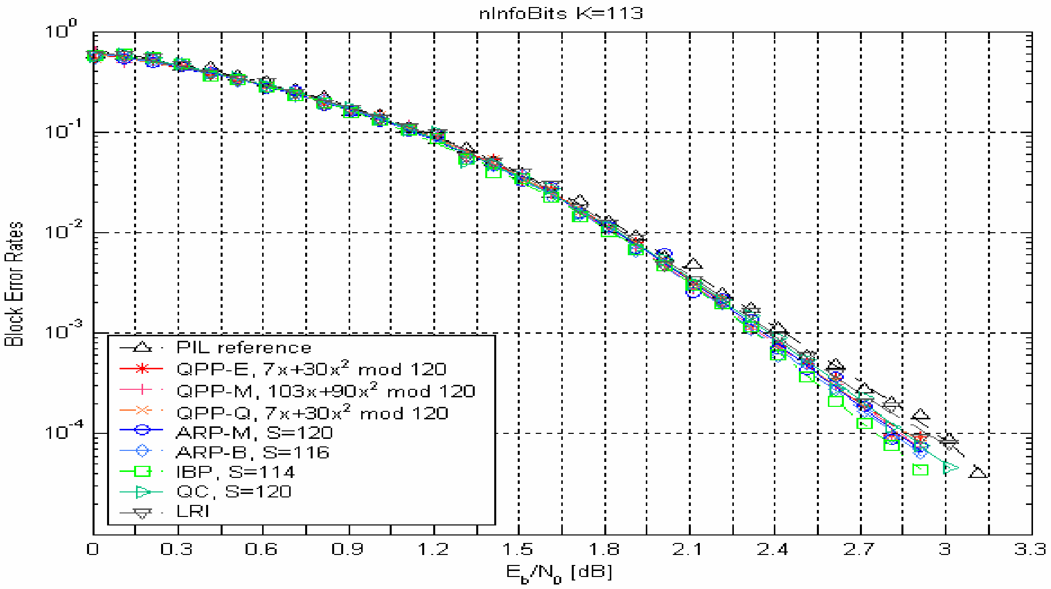


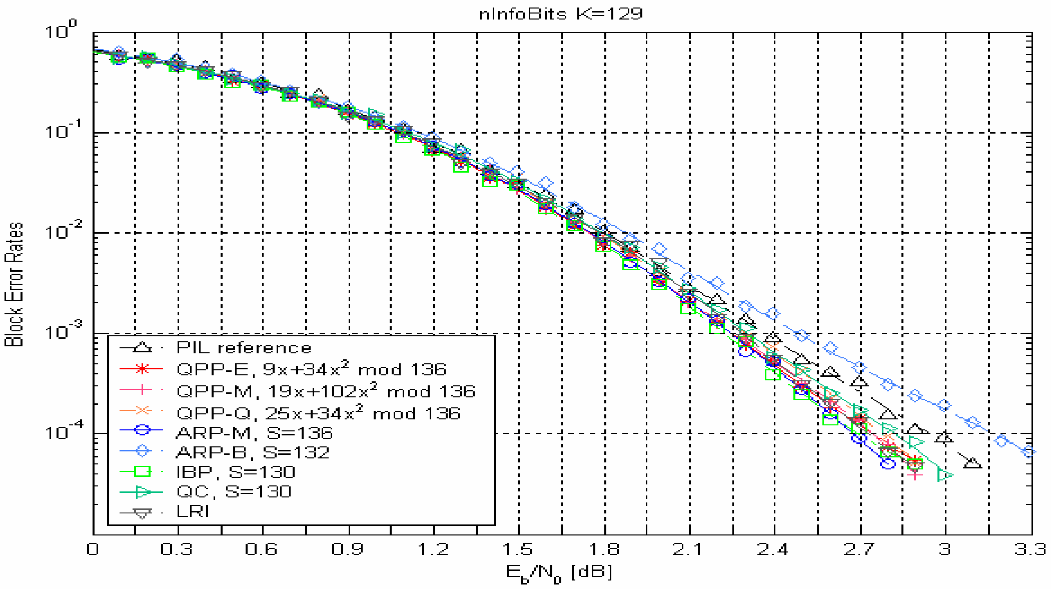

nInfoBits K=52
Block Error Rates
10^0
10^-1
10^-2
10^-3
10^-4
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
4.4
E_b/N_0 [dB]
PIL reference
QPP-E, 10+7x+16x² mod 64
QPP-M, 19x+42x² mod 56
QPP-Q, 1x+28x² mod 56
ARP-M, S=56
ARP-B, S=52
IBP, S=52
QC, S=56
LRI

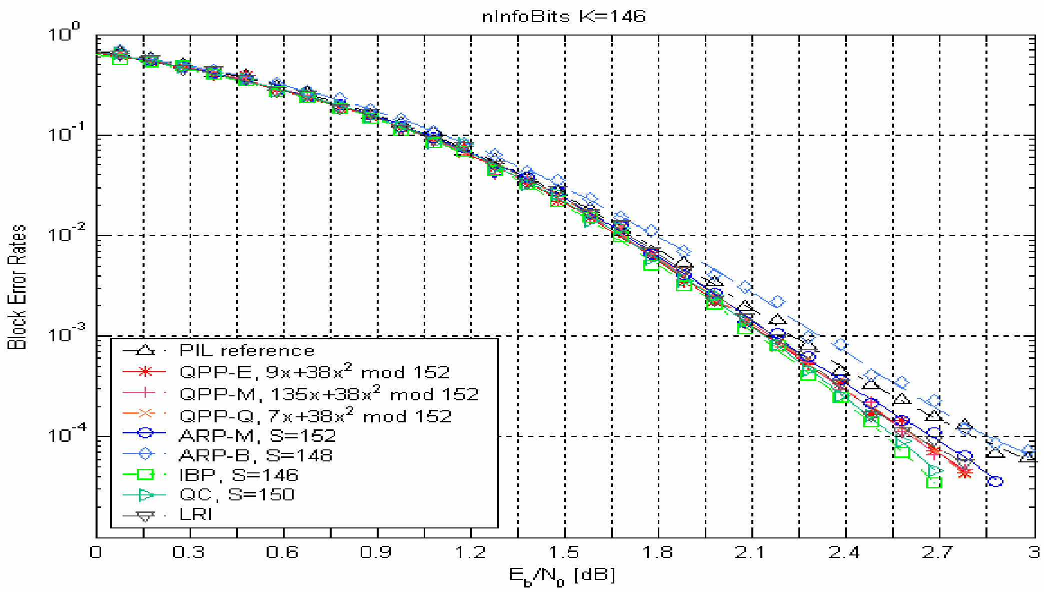

nInfoBits K=67
Block Error Rates
10^0
10^-1
10^-2
10^-3
10^-4
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
E_b/N_0 [dB]
PIL reference
QPP-E, 3+7x+18x² mod 72
QPP-M, 19x+60x² mod 72
QPP-Q, 5x+12x² mod 72
ARP-M, S=72
ARP-B, S=68
IBP, S=68
QC, S=72
LRI

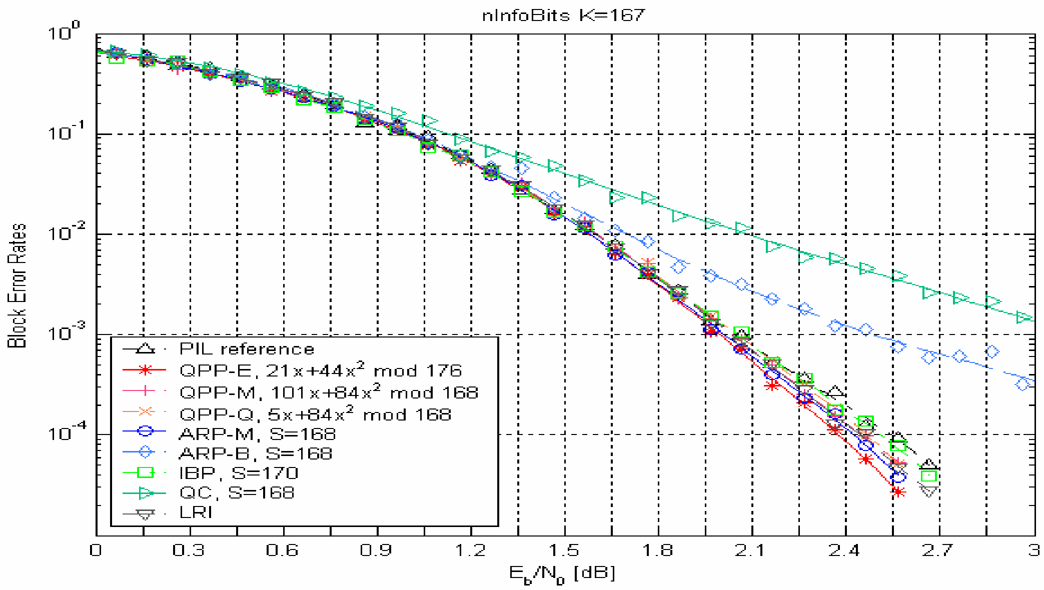

nInfoBits K=87
Block Error Rates
10^0
10^-1
10^-2
10^-3
10^-4
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
E_b/N_0 [dB]
PIL reference
QPP-E, 5x+22x² mod 88
QPP-M, 5x+22x² mod 88
QPP-Q, 5x+22x² mod 88
ARP-M, S=88
ARP-B, S=88
IBP, S=88
QC, S=88
LRI

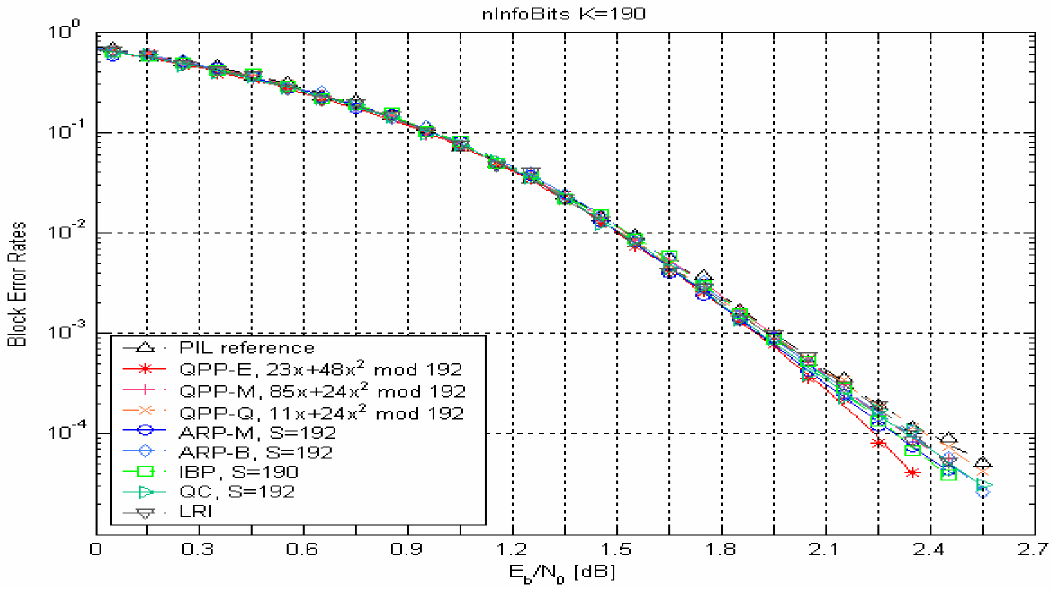

nInfoBits K=99
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PIL reference
QPP-E, $7x+26x^2$ mod 104
QPP-M, $45x+26x^2$ mod 104
QPP-Q, $7x+26x^2$ mod 104
ARP-M, S=104
ARP-B, S=100
IBP, S=100
QC, S=100
LRI
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3
3.3
E_b/N_0 [dB]

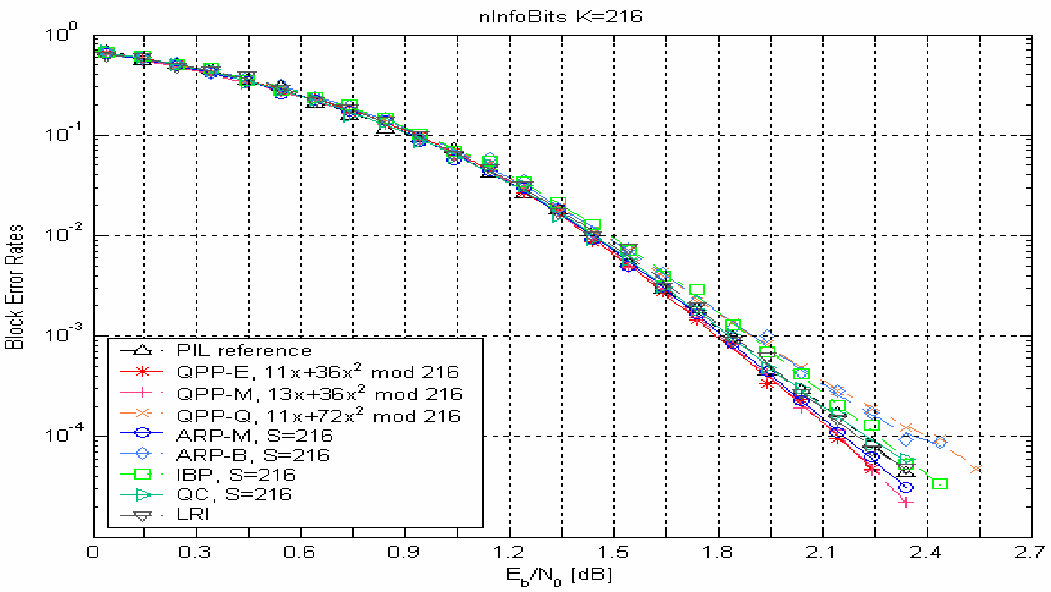

nInfoBits K=113
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PIL reference
QPP-E, $7x+30x^2$ mod 120
QPP-M, $103x+90x^2$ mod 120
QPP-Q, $7x+30x^2$ mod 120
ARP-M, S=120
ARP-B, S=116
IBP, S=114
QC, S=120
LRI
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3
3.3
E_b/N_0 [dB]

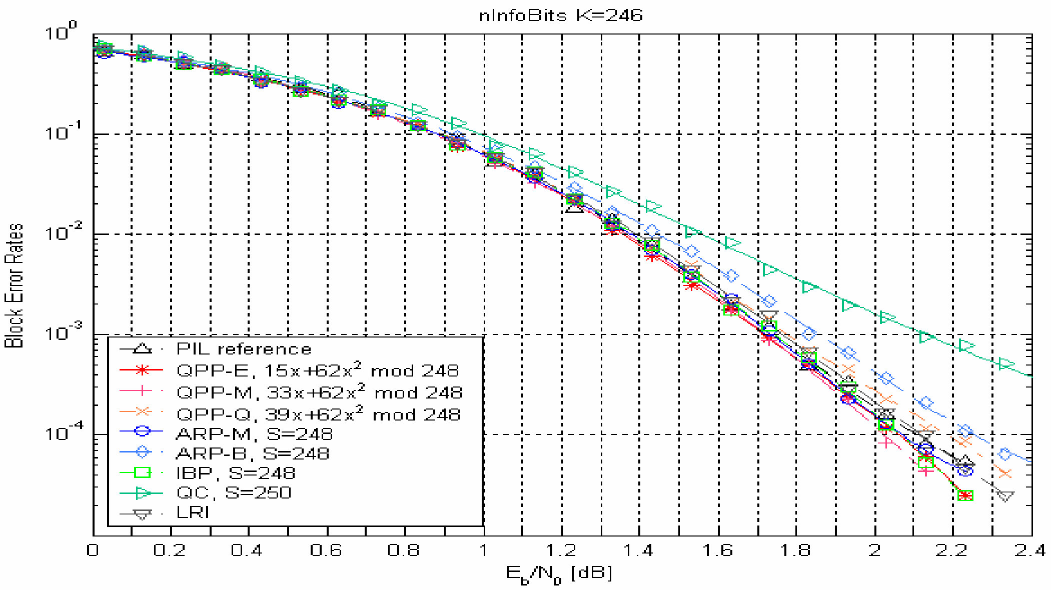

nInfoBits K=129
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PIL reference
QPP-E, $9x+34x^2$ mod 136
QPP-M, $19x+102x^2$ mod 136
QPP-Q, $25x+34x^2$ mod 136
ARP-M, S=136
ARP-B, S=132
IBP, S=130
QC, S=130
LRI
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3
3.3
E_b/N_0 [dB]

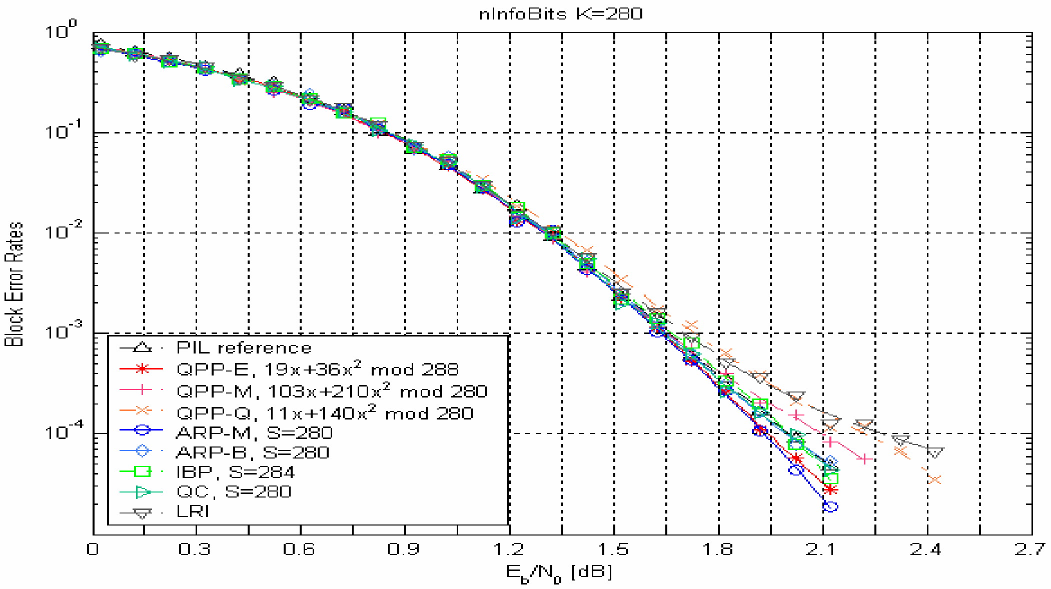

nInfoBits K=146
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3
E_b/N_0 [dB]
PIL reference
QPP-E, $9x+38x^2$ mod 152
QPP-M, $135x+38x^2$ mod 152
QPP-Q, $7x+38x^2$ mod 152
ARP-M, S=152
ARP-B, S=148
IBP, S=146
QC, S=150
LRI

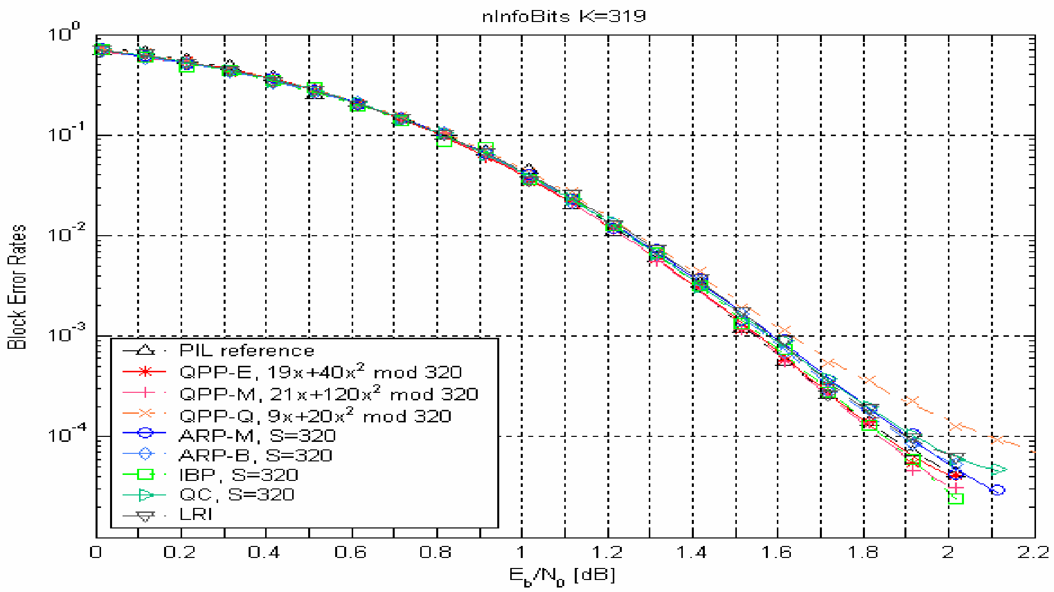

nInfoBits K=167
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3
E_b/N_0 [dB]
PIL reference
QPP-E, $21x+44x^2$ mod 176
QPP-M, $101x+84x^2$ mod 168
QPP-Q, $5x+84x^2$ mod 168
ARP-M, S=168
ARP-B, S=168
IBP, S=170
QC, S=168
LRI

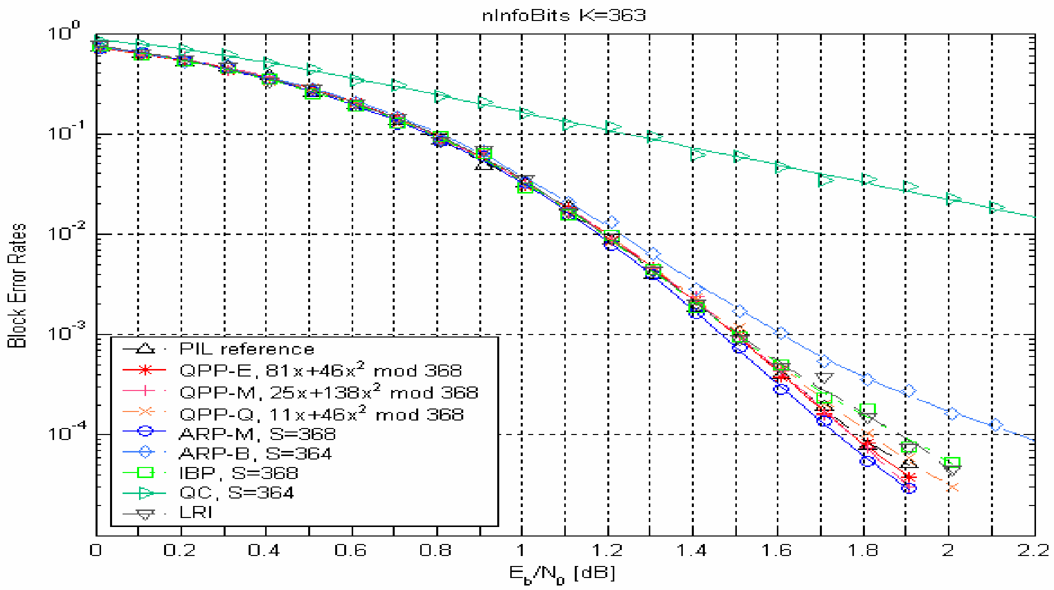

nInfoBits K=190
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
E_b/N_0 [dB]
PIL reference
QPP-E, $23x+48x^2$ mod 192
QPP-M, $85x+24x^2$ mod 192
QPP-Q, $11x+24x^2$ mod 192
ARP-M, S=192
ARP-B, S=192
IBP, S=190
QC, S=192
LRI

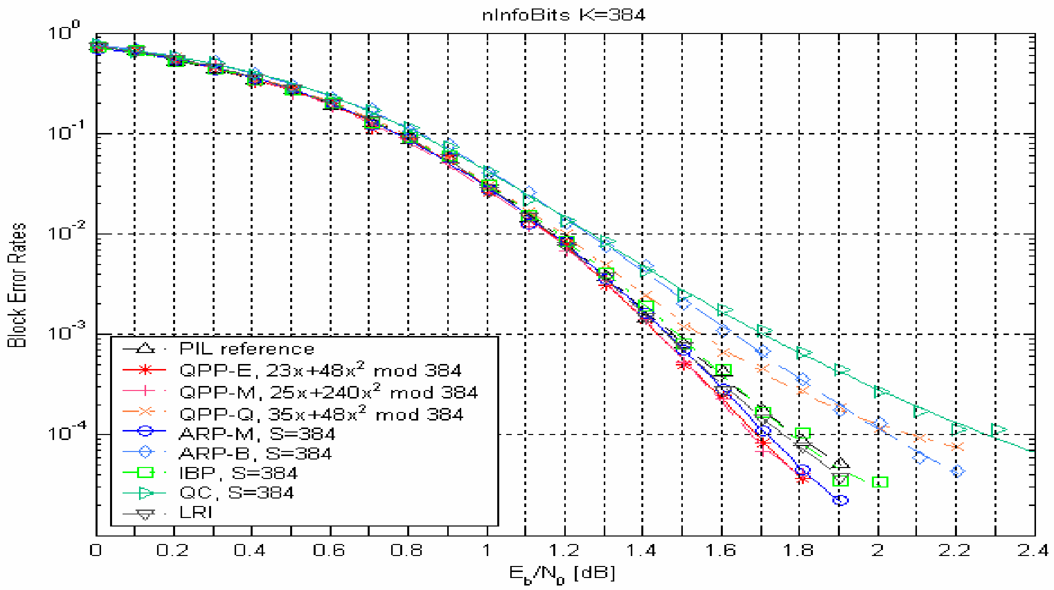

nInfoBits K=216
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
E_b/N_0 [dB]
PIL reference
QPP-E, $11x+36x^2$ mod 216
QPP-M, $13x+36x^2$ mod 216
QPP-Q, $11x+72x^2$ mod 216
ARP-M, S=216
ARP-B, S=216
IBP, S=216
QC, S=216
LRI

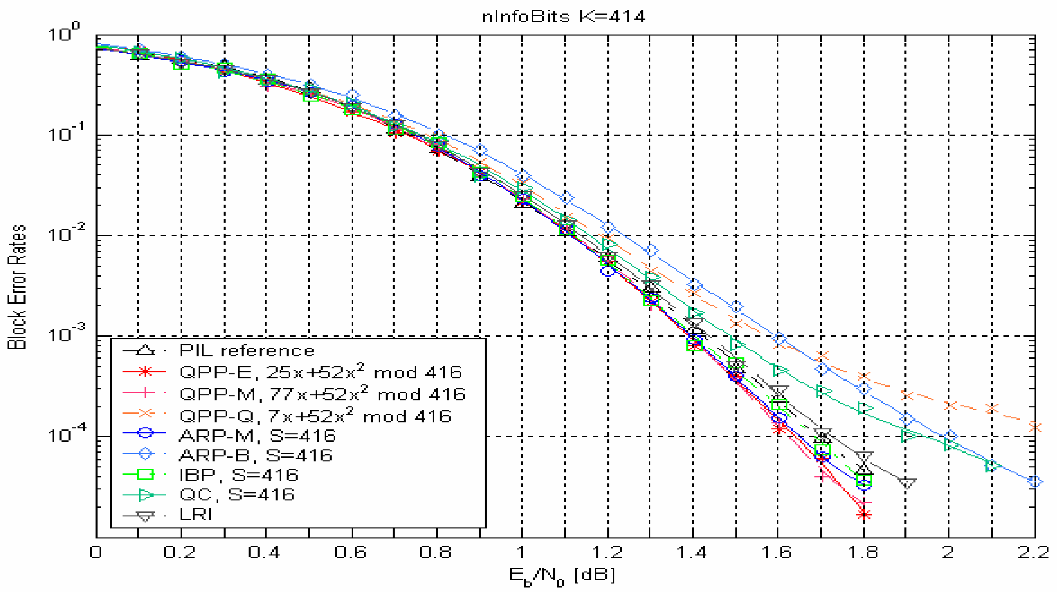

nInfoBits K=246
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
E_b/N_0 [dB]
PIL reference
QPP-E, $15x+62x^2$ mod 248
QPP-M, $33x+62x^2$ mod 248
QPP-Q, $39x+62x^2$ mod 248
ARP-M, S=248
ARP-B, S=248
IBP, S=248
QC, S=250
LRI

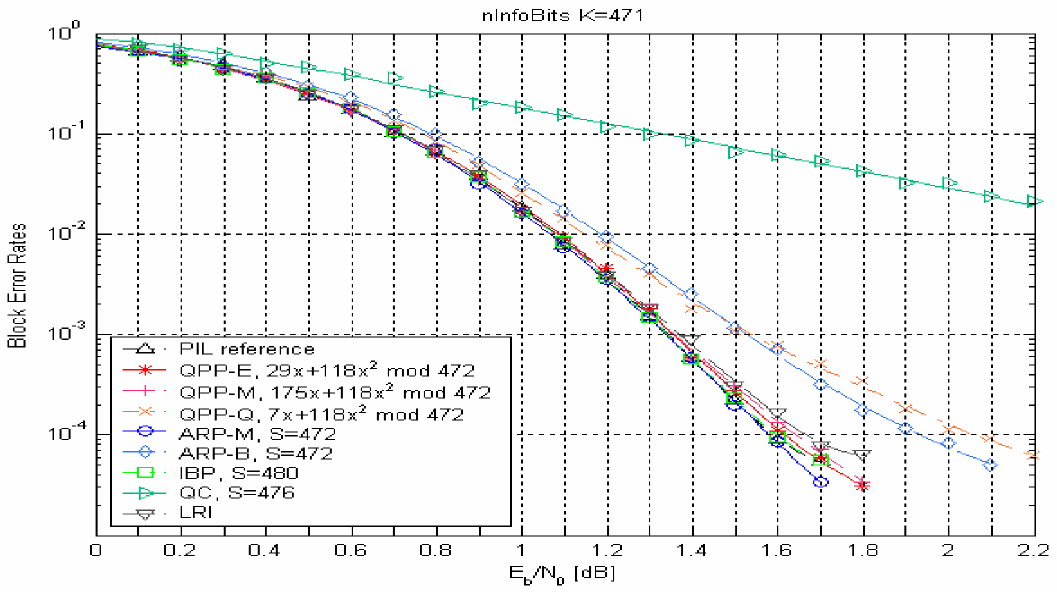

nInfoBits K=280
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
E_b/N_0 [dB]
PIL reference
QPP-E, $19x+36x^2$ mod 288
QPP-M, $103x+210x^2$ mod 280
QPP-Q, $11x+140x^2$ mod 280
ARP-M, S=280
ARP-B, S=280
IBP, S=284
QC, S=280
LRI

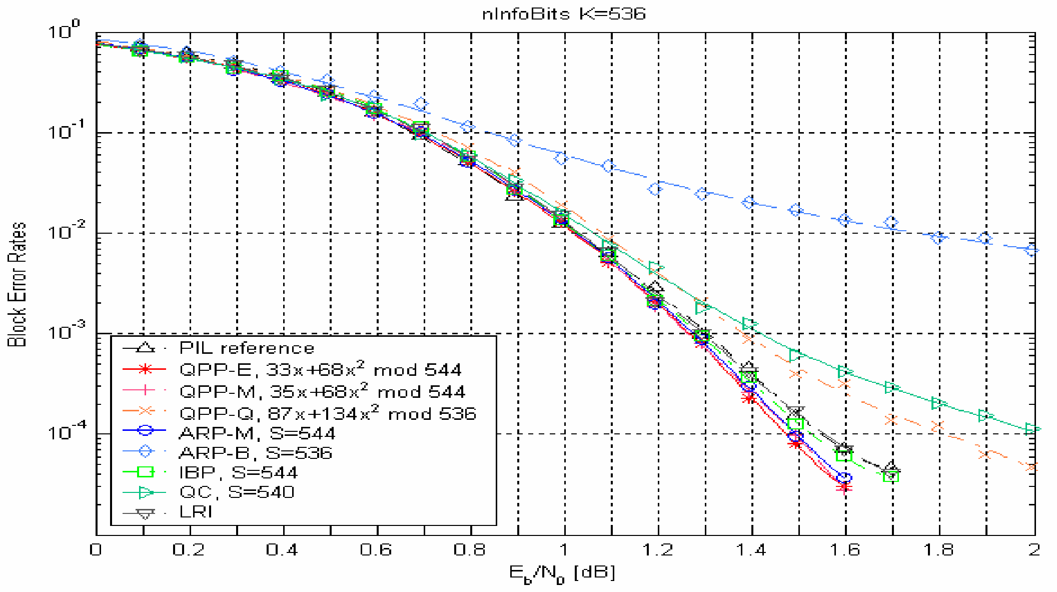

nInfoBits K=319

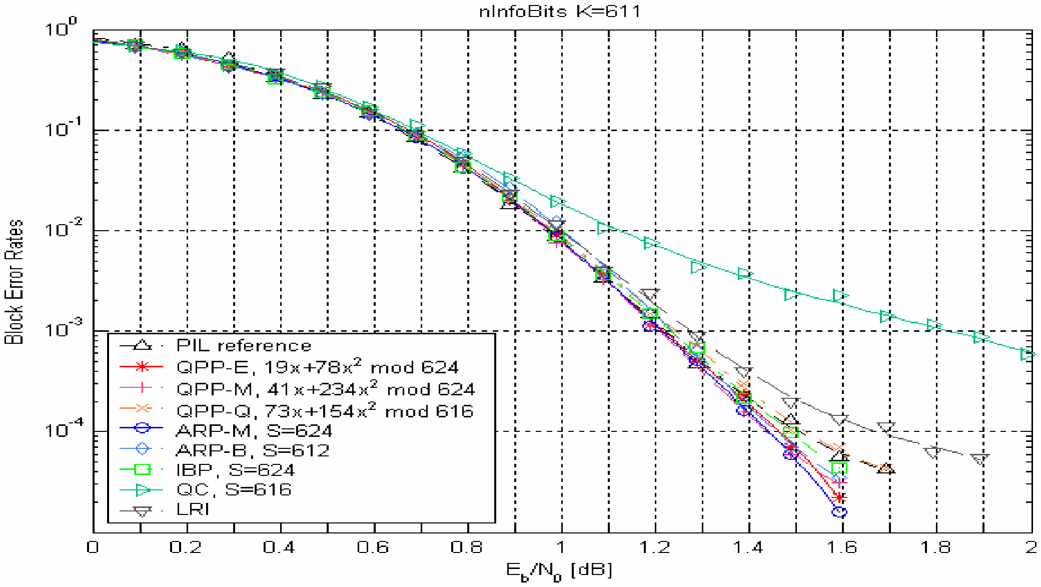

nInfoBits K=363

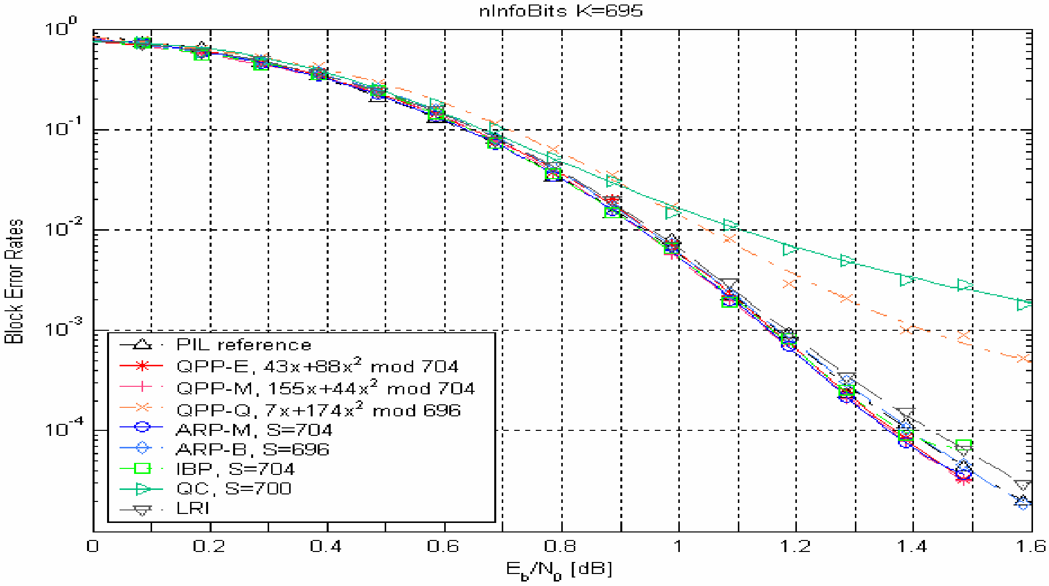

nInfoBits K=384


nInfoBits K=414
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
E_b/N_0 [dB]
PIL reference
QPP-E, $25x+52x^2$ mod 416
QPP-M, $77x+52x^2$ mod 416
QPP-Q, $7x+52x^2$ mod 416
ARP-M, S=416
ARP-B, S=416
IBP, S=416
QC, S=416
LRI


nInfoBits K=471
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
E_b/N_0 [dB]
PIL reference
QPP-E, $29x+118x^2$ mod 472
QPP-M, $175x+118x^2$ mod 472
QPP-Q, $7x+118x^2$ mod 472
ARP-M, S=472
ARP-B, S=472
IBP, S=480
QC, S=476
LRI


nInfoBits K=536
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
E_b/N_0 [dB]
PIL reference
QPP-E, $33x+68x^2$ mod 544
QPP-M, $35x+68x^2$ mod 544
QPP-Q, $87x+134x^2$ mod 536
ARP-M, S=544
ARP-B, S=536
IBP, S=544
QC, S=540
LRI


nInfoBits K=611
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
E_b/N_0 [dB]
PIL reference
QPP-E, $19x+78x^2$ mod 624
QPP-M, $41x+234x^2$ mod 624
QPP-Q, $73x+154x^2$ mod 616
ARP-M, S=624
ARP-B, S=612
IBP, S=624
QC, S=616
LRI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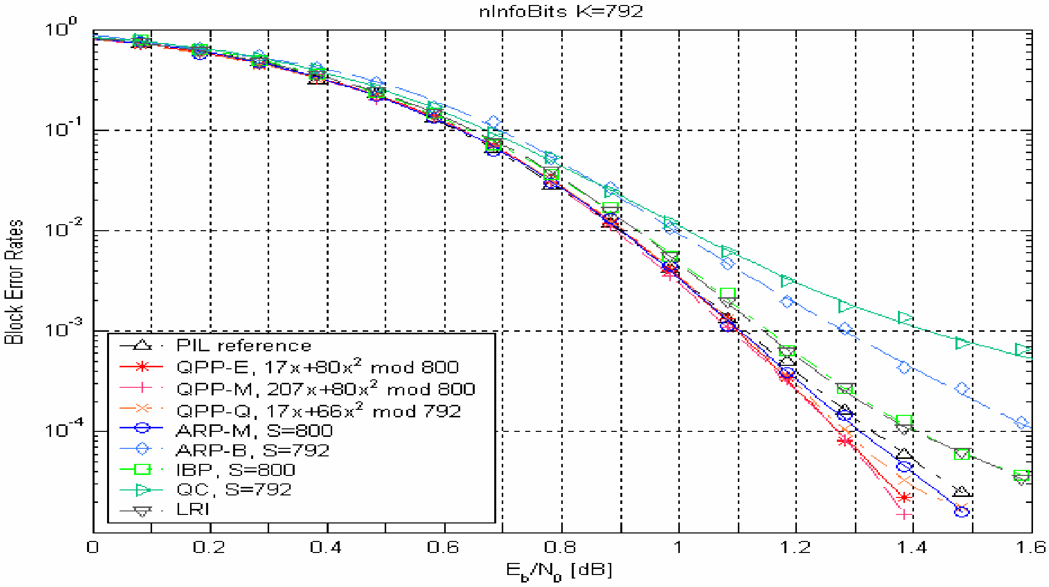
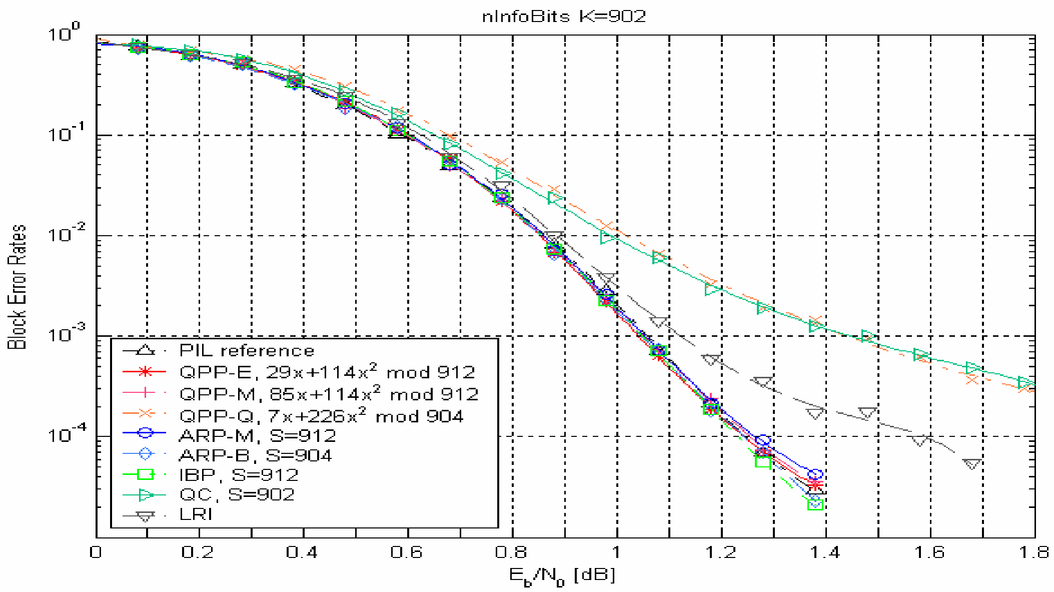
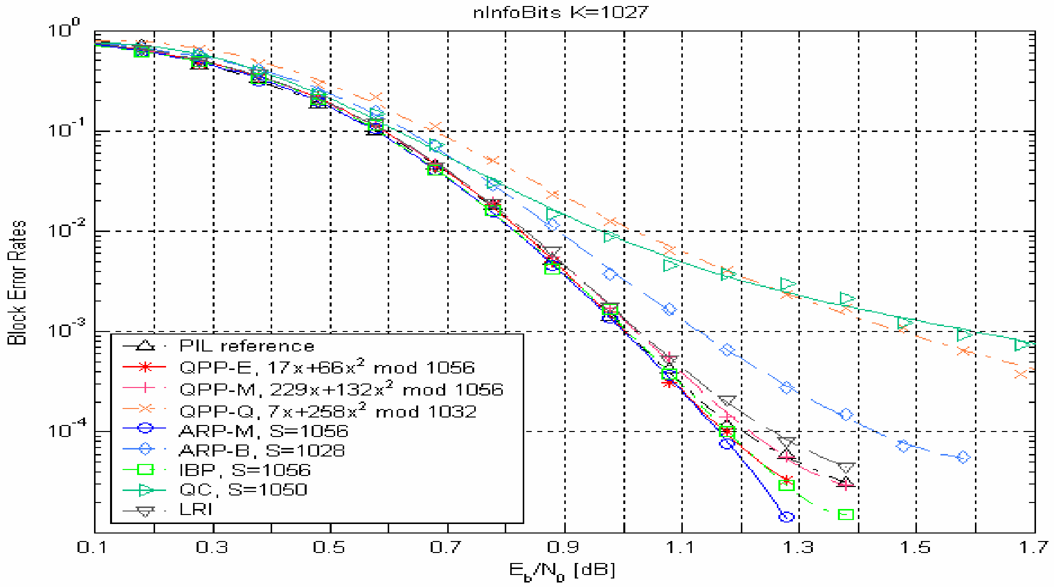
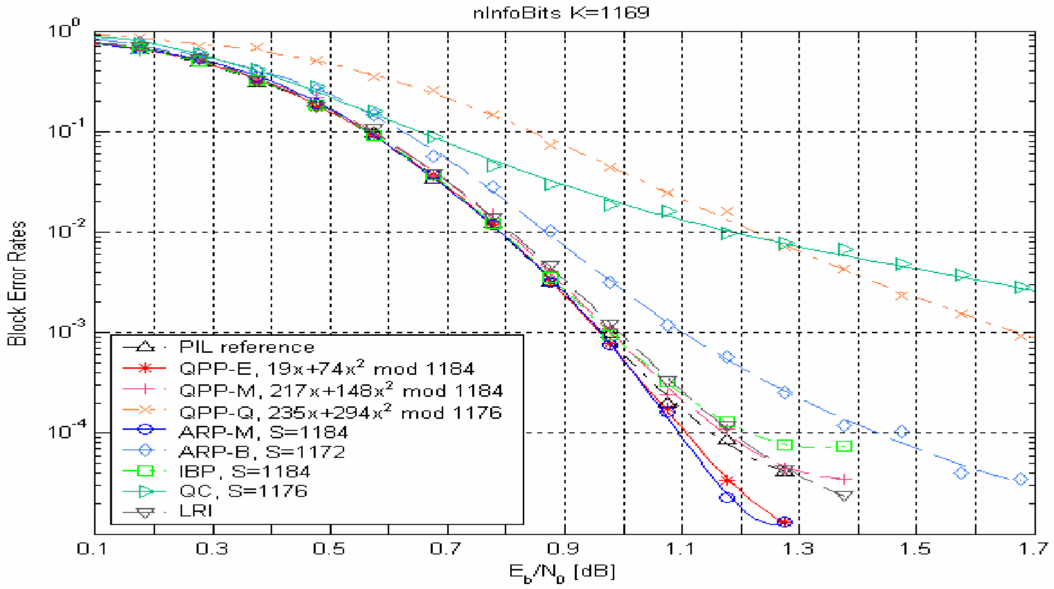
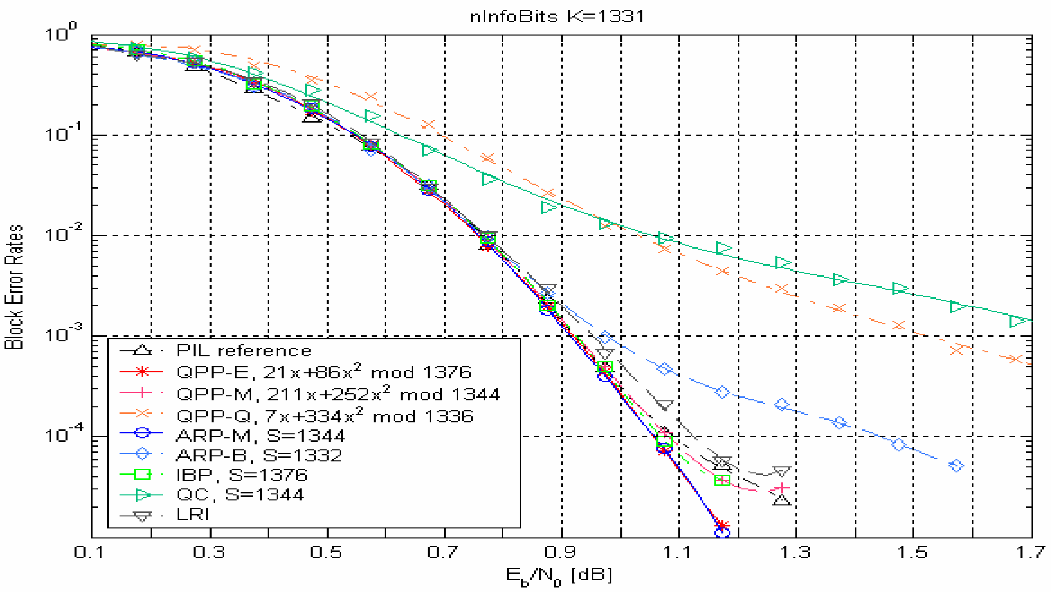
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
E_b/N_0 [dB]
PIL reference
QPP-E, $43x+88x^2$ mod 704
QPP-M, $155x+44x^2$ mod 704
QPP-Q, $7x+174x^2$ mod 696
ARP-M, S=704
ARP-B, S=696
IBP, S=704
QC, S=700
LRI

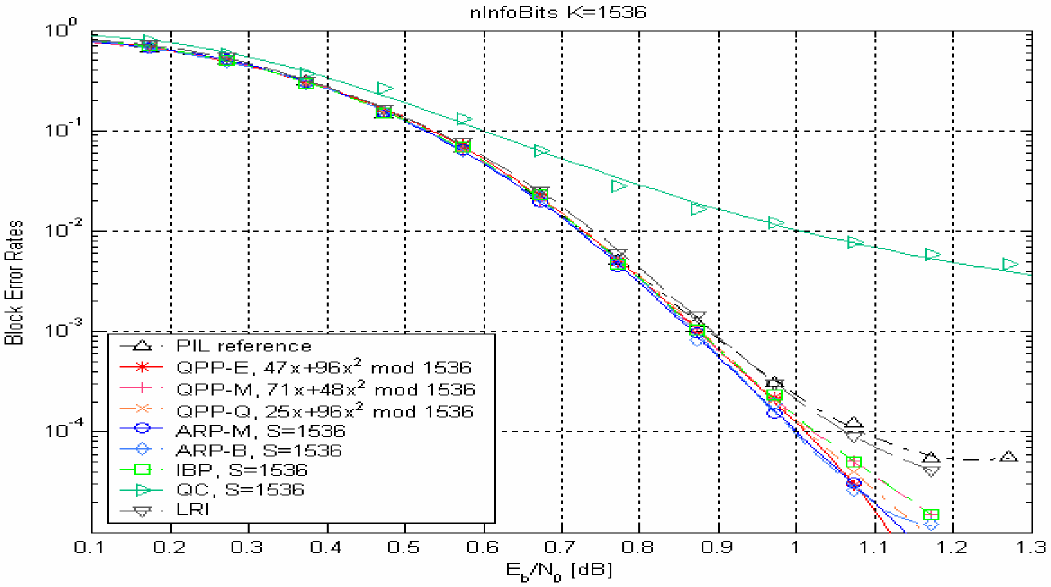

nInfoBits K=792
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
E_b/N_0 [dB]
PIL reference
QPP-E, $17x+80x^2$ mod 800
QPP-M, $207x+80x^2$ mod 800
QPP-Q, $17x+66x^2$ mod 792
ARP-M, S=800
ARP-B, S=792
IBP, S=800
QC, S=792
LRI

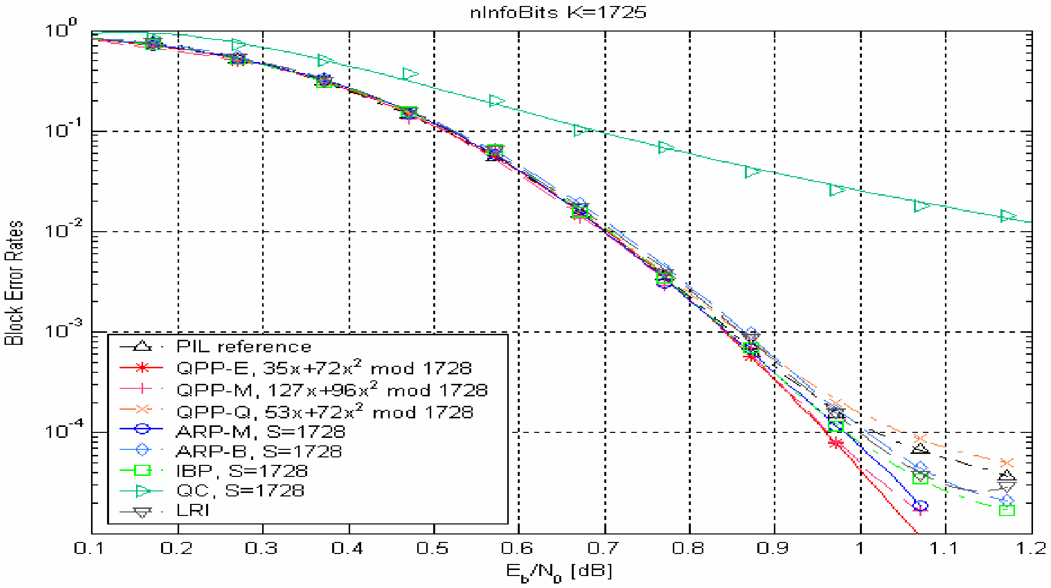

nInfoBits K=902

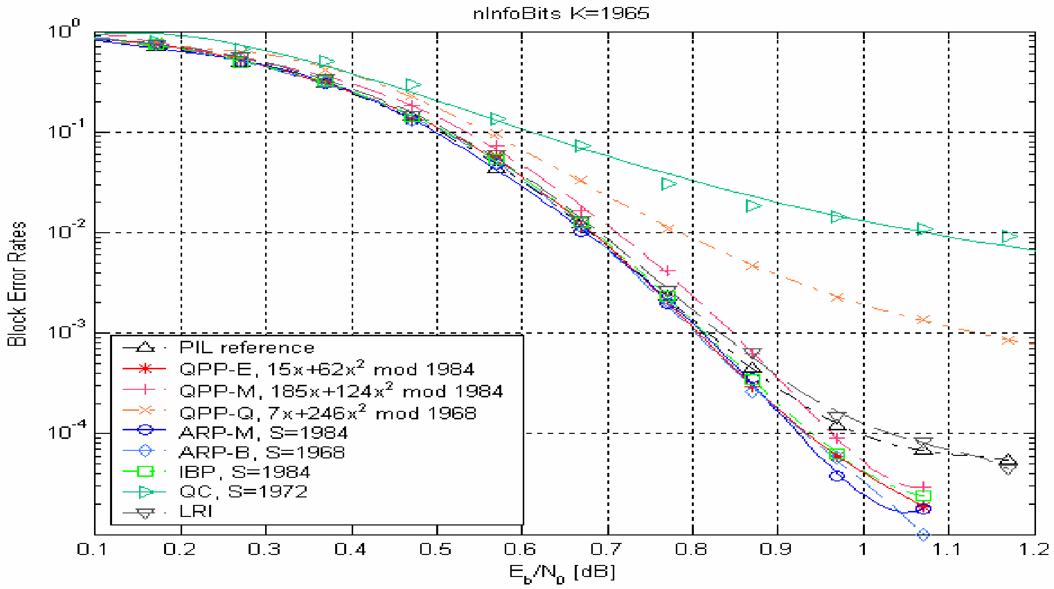

nInfoBits K=1027

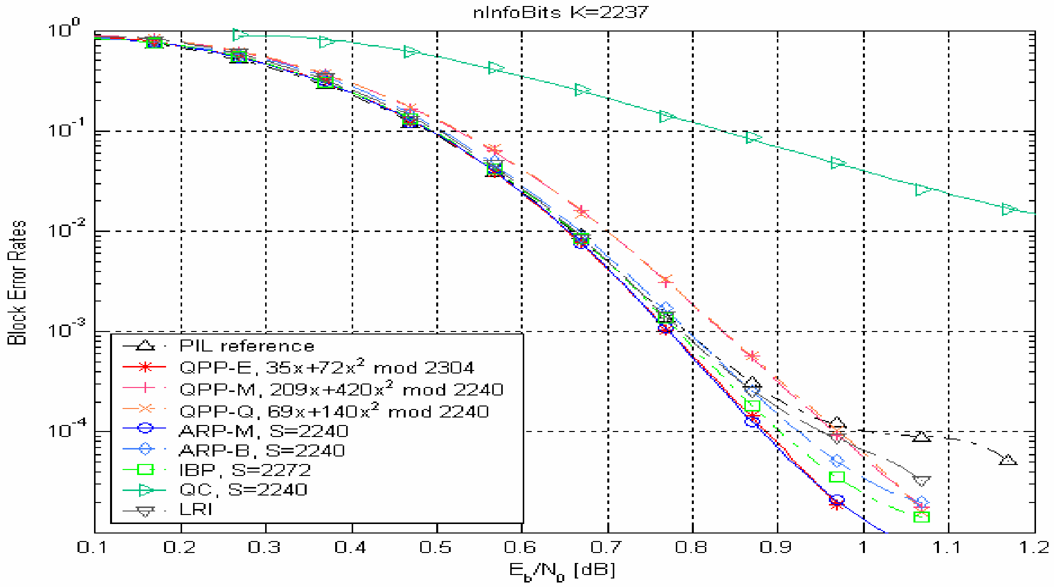

nInfoBits K=1169

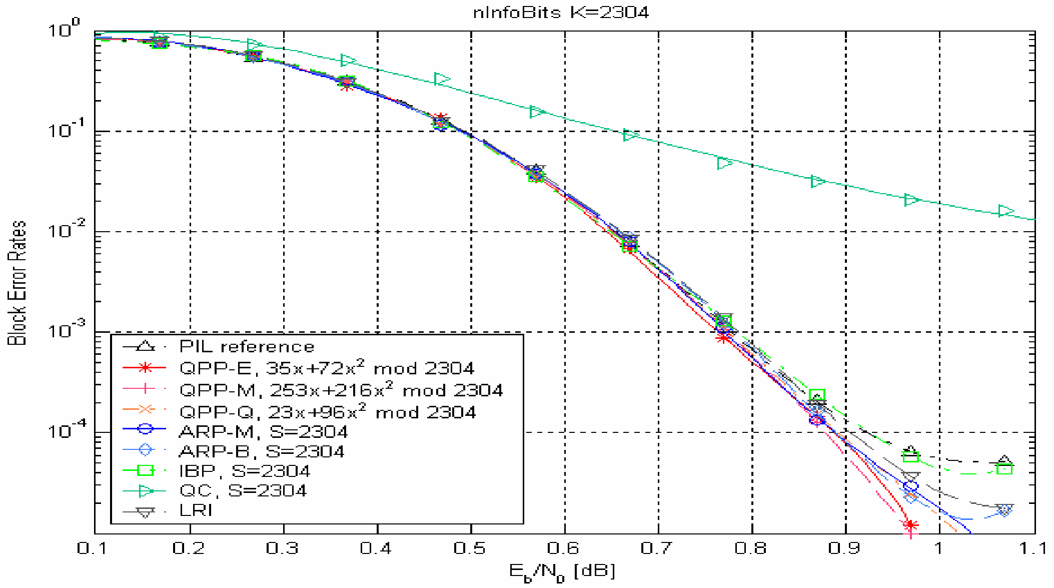

nInfoBits K=1331
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
E_b/N_0 [dB]
PIL reference
QPP-E, $21x+86x^2$ mod 1376
QPP-M, $211x+252x^2$ mod 1344
QPP-Q, $7x+334x^2$ mod 1336
ARP-M, S=1344
ARP-B, S=1332
IBP, S=1376
QC, S=1344
LRI

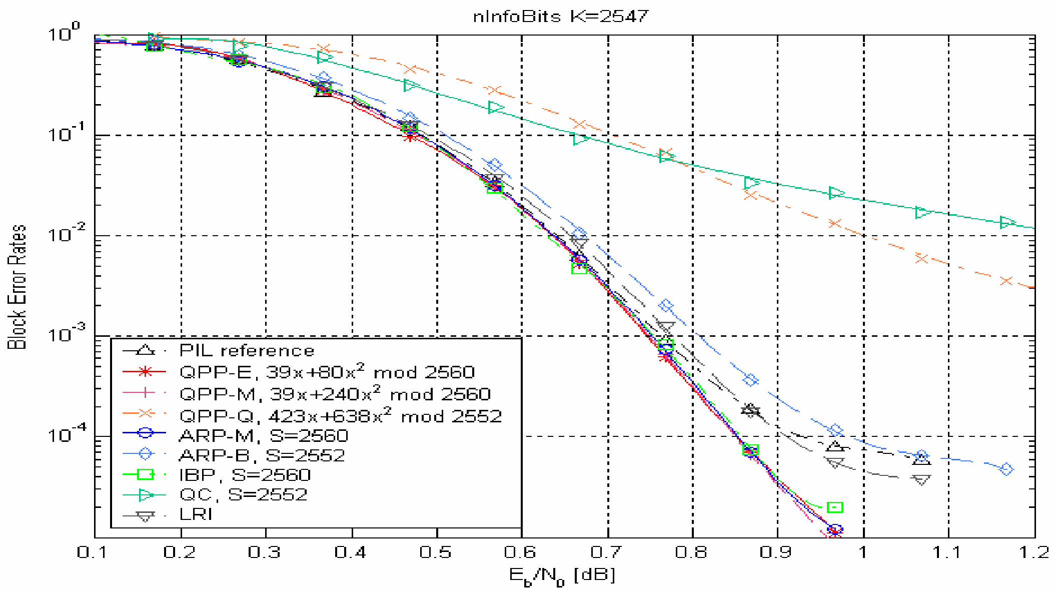

nInfoBits K=1536
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
E_b/N_0 [dB]
PIL reference
QPP-E, $47x+96x^2$ mod 1536
QPP-M, $71x+48x^2$ mod 1536
QPP-Q, $25x+96x^2$ mod 1536
ARP-M, S=1536
ARP-B, S=1536
IBP, S=1536
QC, S=1536
LRI

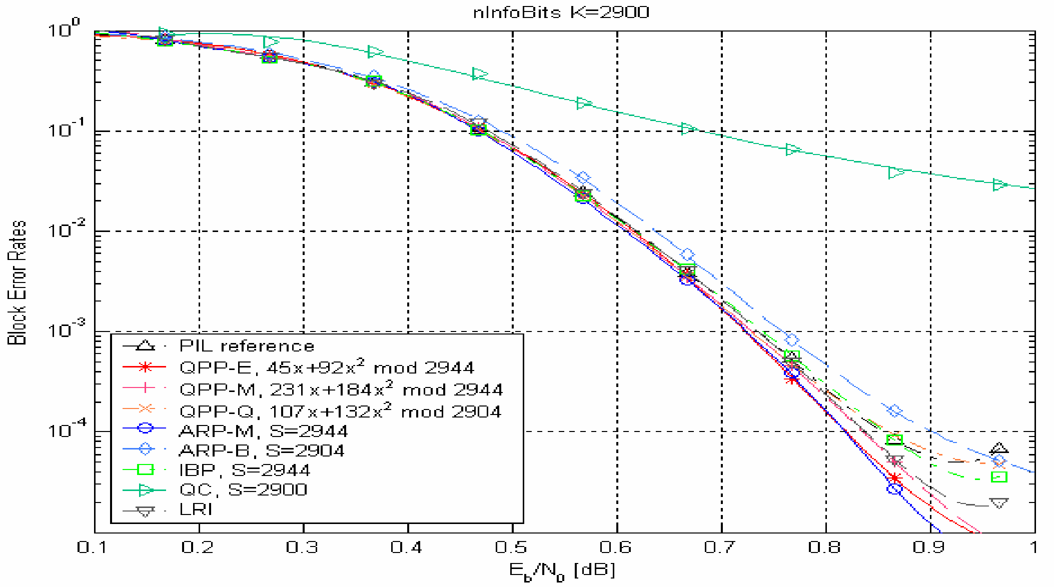

nInfoBits K=1725
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
E_b/N_0 [dB]
PIL reference
QPP-E, $35x+72x^2$ mod 1728
QPP-M, $127x+96x^2$ mod 1728
QPP-Q, $53x+72x^2$ mod 1728
ARP-M, S=1728
ARP-B, S=1728
IBP, S=1728
QC, S=1728
LRI

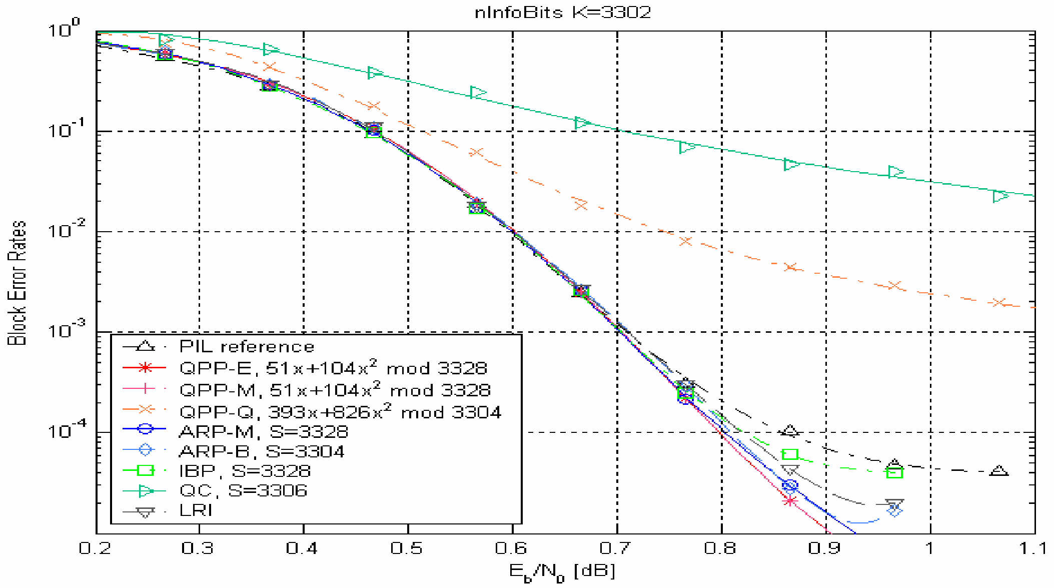

nInfoBits K=1965
Block Error Rates
10^0
10^-1
10^-2
10^-3
10^-4
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2
E_b/N_0 [dB]
PIL reference
QPP-E, 15x+62x² mod 1984
QPP-M, 185x+124x² mod 1984
QPP-Q, 7x+246x² mod 1968
ARP-M, S=1984
ARP-B, S=1968
IBP, S=1984
QC, S=1972
LRI

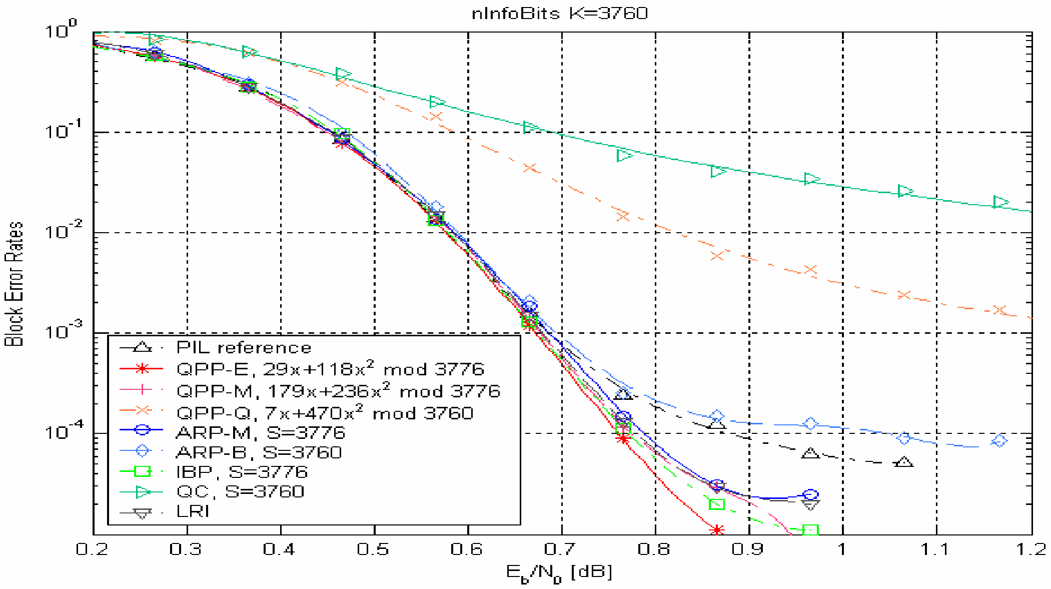

nInfoBits K=2237
Block Error Rates
10^0
10^-1
10^-2
10^-3
10^-4
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2
E_b/N_0 [dB]
PIL reference
QPP-E, 35x+72x² mod 2304
QPP-M, 209x+420x² mod 2240
QPP-Q, 69x+140x² mod 2240
ARP-M, S=2240
ARP-B, S=2240
IBP, S=2272
QC, S=2240
LRI

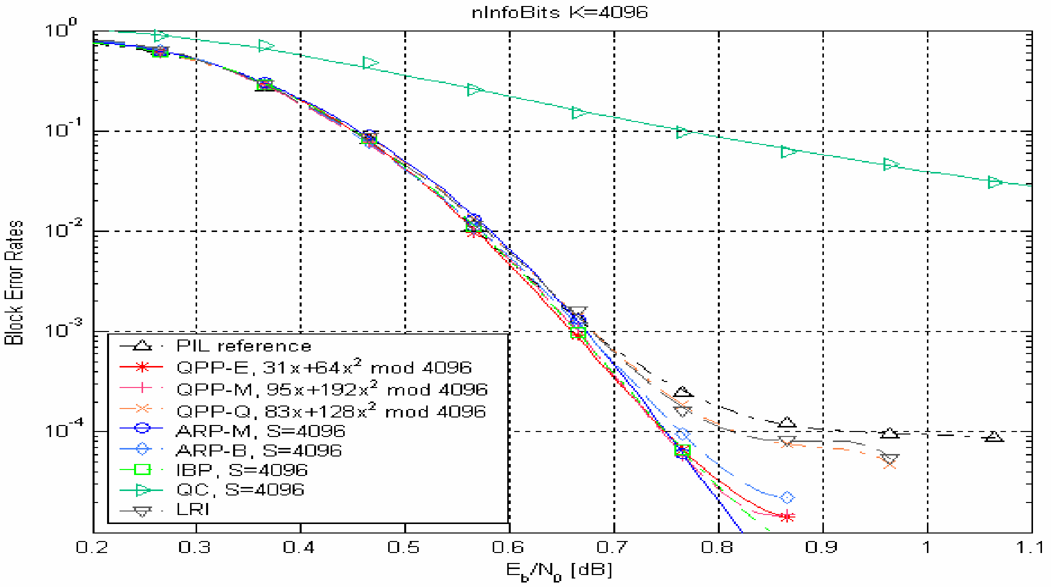

nInfoBits K=2304
Block Error Rates
10^0
10^-1
10^-2
10^-3
10^-4
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1
E_b/N_0 [dB]
PIL reference
QPP-E, 35x+72x² mod 2304
QPP-M, 253x+216x² mod 2304
QPP-Q, 23x+96x² mod 2304
ARP-M, S=2304
ARP-B, S=2304
IBP, S=2304
QC, S=2304
LRI

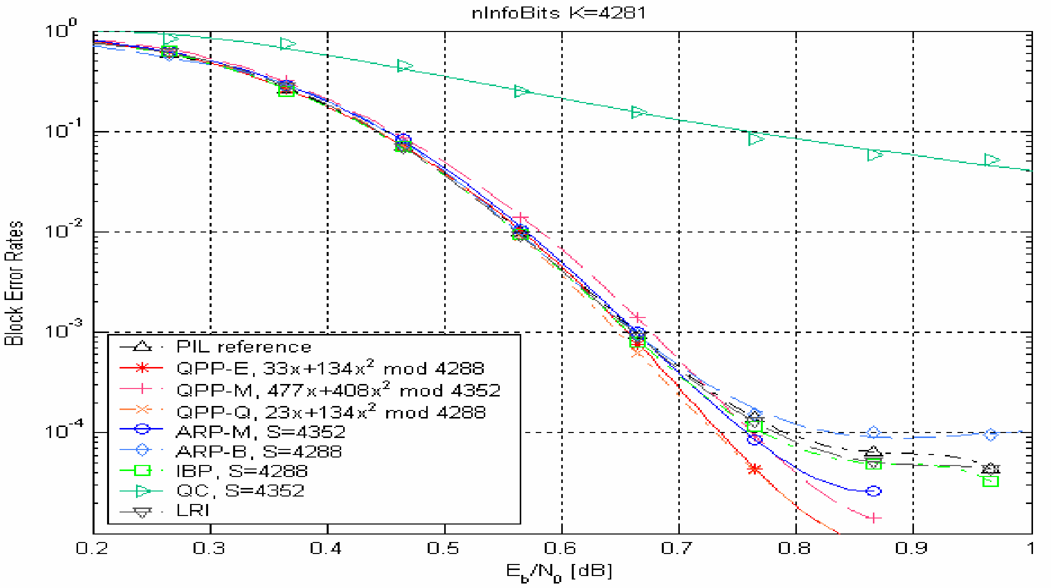

nInfoBits K=2547
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PIL reference
QPP-E, 39x+80x^2 mod 2560
QPP-M, 39x+240x^2 mod 2560
QPP-Q, 423x+638x^2 mod 2552
ARP-M, S=2560
ARP-B, S=2552
IBP, S=2560
QC, S=2552
LRI
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
E$_b$/N$_0$ [dB]

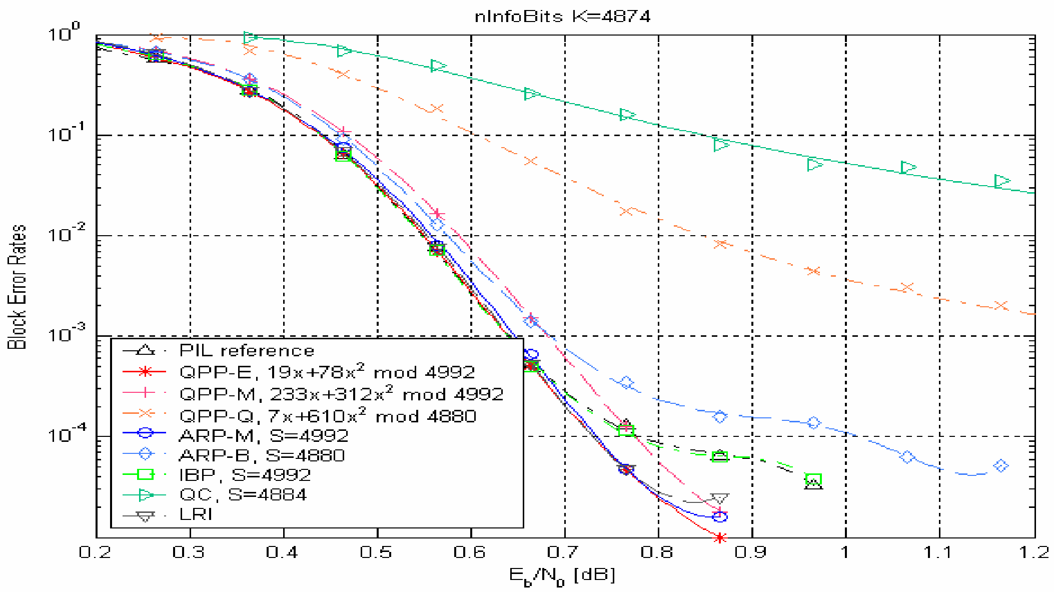

nInfoBits K=2900
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PIL reference
QPP-E, 45x+92x^2 mod 2944
QPP-M, 231x+184x^2 mod 2944
QPP-Q, 107x+132x^2 mod 2904
ARP-M, S=2944
ARP-B, S=2904
IBP, S=2944
QC, S=2900
LRI
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
E$_b$/N$_0$ [dB]

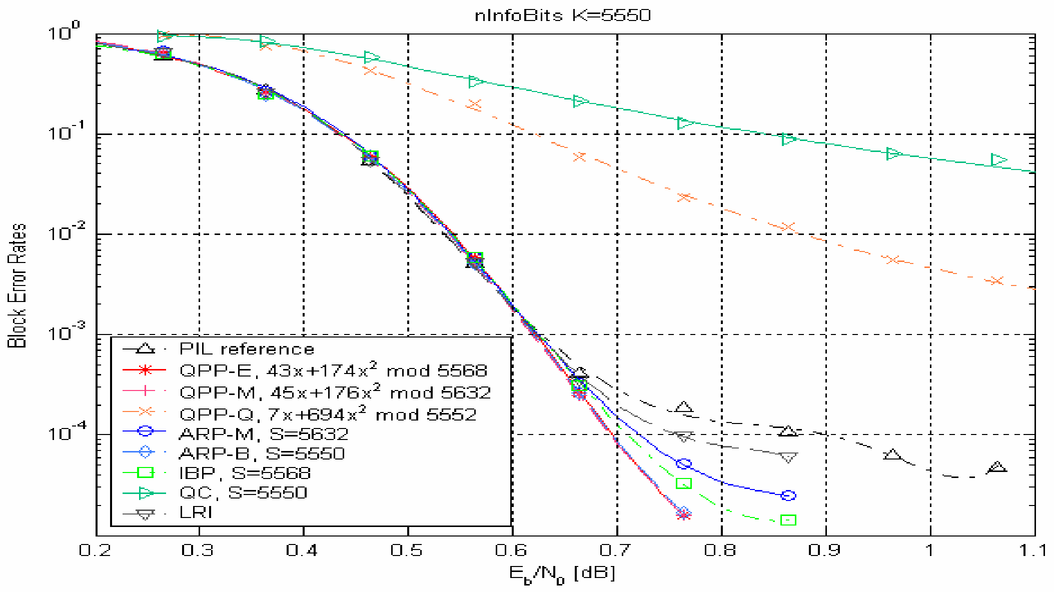

nInfoBits K=3302
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PIL reference
QPP-E, 51x+104x^2 mod 3328
QPP-M, 51x+104x^2 mod 3328
QPP-Q, 393x+826x^2 mod 3304
ARP-M, S=3328
ARP-B, S=3304
IBP, S=3328
QC, S=3306
LRI
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
E$_b$/N$_0$ [dB]

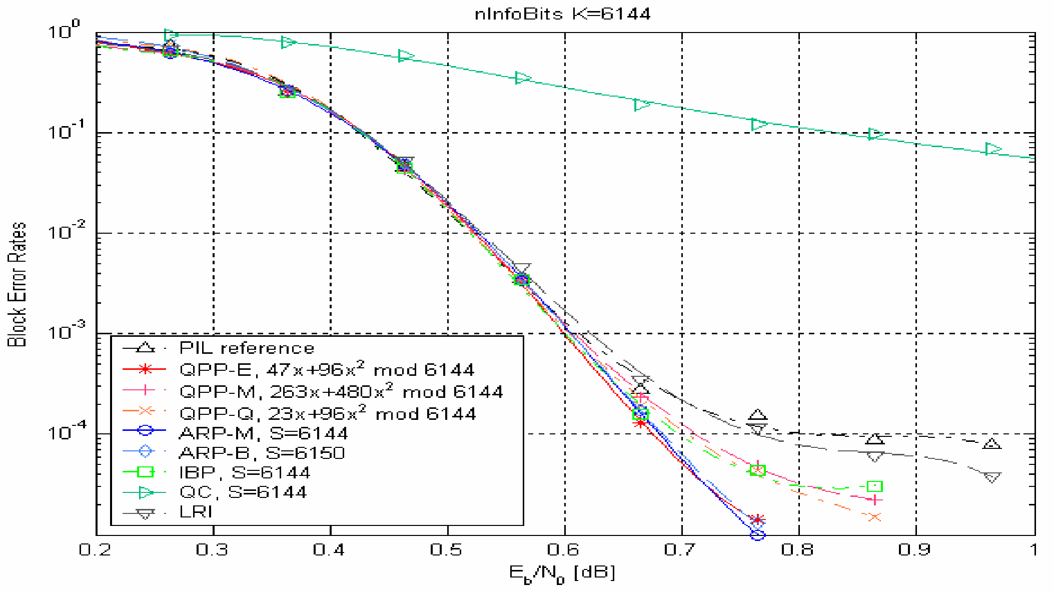

nInfoBits K=3760
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PIL reference
QPP-E, 29x+118x^2 mod 3776
QPP-M, 179x+236x^2 mod 3776
QPP-Q, 7x+470x^2 mod 3760
ARP-M, S=3776
ARP-B, S=3760
IBP, S=3776
QC, S=3760
LRI
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
E_b/N_0 [dB]

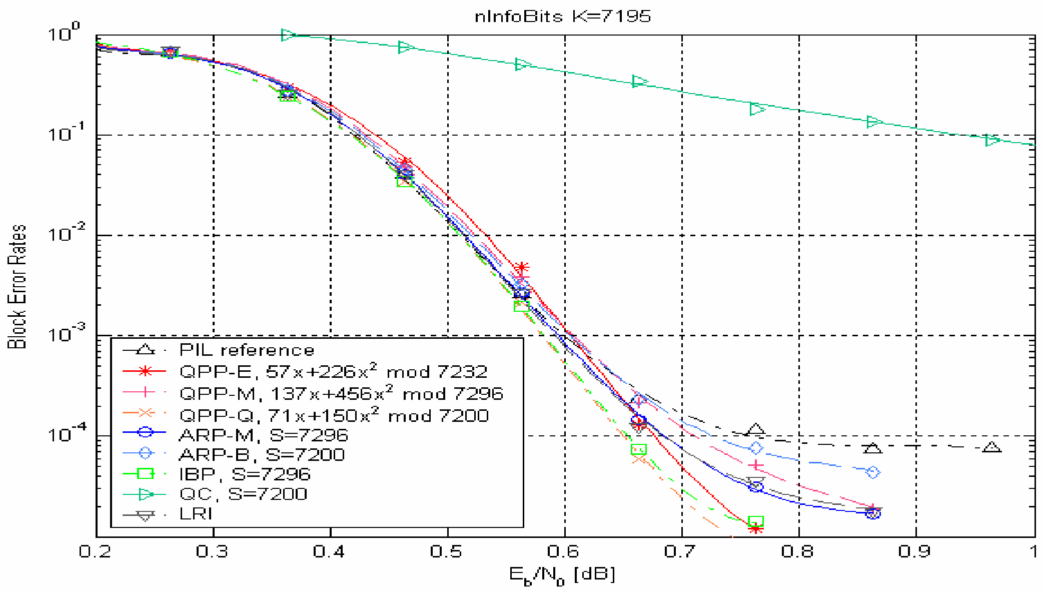

nInfoBits K=4096
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PIL reference
QPP-E, 31x+64x^2 mod 4096
QPP-M, 95x+192x^2 mod 4096
QPP-Q, 83x+128x^2 mod 4096
ARP-M, S=4096
ARP-B, S=4096
IBP, S=4096
QC, S=4096
LRI
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
E_b/N_0 [dB]

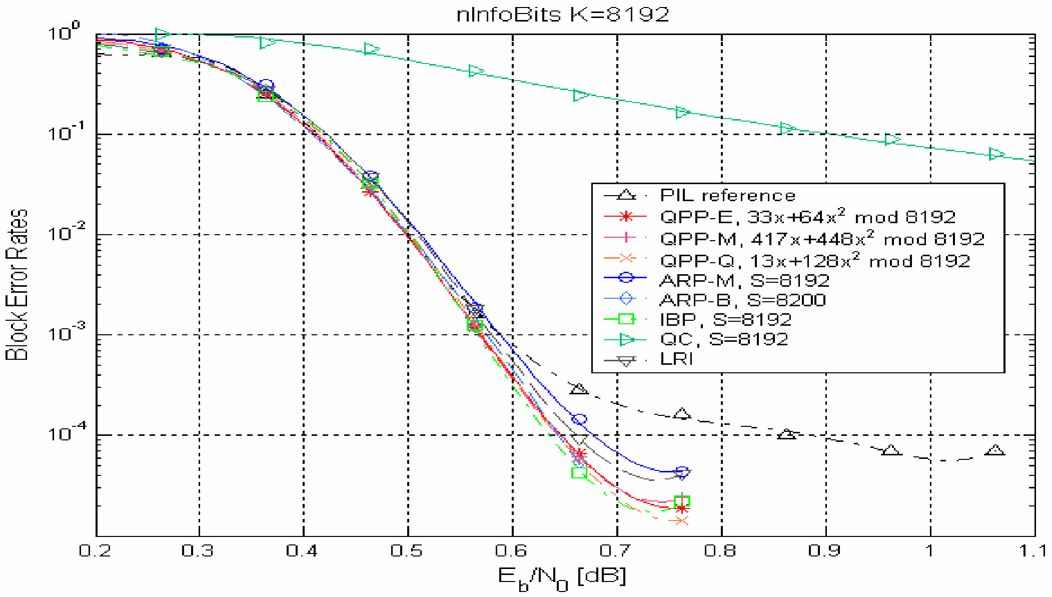

nInfoBits K=4281
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PIL reference
QPP-E, 33x+134x^2 mod 4288
QPP-M, 477x+408x^2 mod 4352
QPP-Q, 23x+134x^2 mod 4288
ARP-M, S=4352
ARP-B, S=4288
IBP, S=4288
QC, S=4352
LRI
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
E_b/N_0 [dB]


nInfoBits K=4874
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
E_b/N_0 [dB]
PIL reference
QPP-E, $19x+78x^2$ mod 4992
QPP-M, $233x+312x^2$ mod 4992
QPP-Q, $7x+610x^2$ mod 4880
ARP-M, S=4992
ARP-B, S=4880
IBP, S=4992
QC, S=4884
LRI

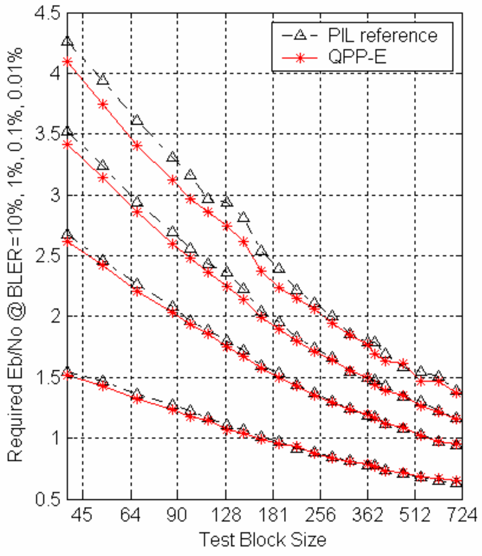

nInfoBits K=5550
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
E_b/N_0 [dB]
PIL reference
QPP-E, $43x+174x^2$ mod 5568
QPP-M, $45x+176x^2$ mod 5632
QPP-Q, $7x+694x^2$ mod 5552
ARP-M, S=5632
ARP-B, S=5550
IBP, S=5568
QC, S=5550
LRI

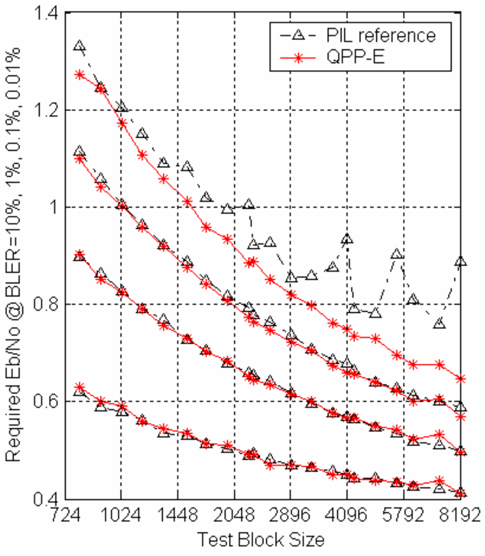

nInfoBits K=6144
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
E_b/N_0 [dB]
PIL reference
QPP-E, $47x+96x^2$ mod 6144
QPP-M, $263x+480x^2$ mod 6144
QPP-Q, $23x+96x^2$ mod 6144
ARP-M, S=6144
ARP-B, S=6150
IBP, S=6144
QC, S=6144
LRI

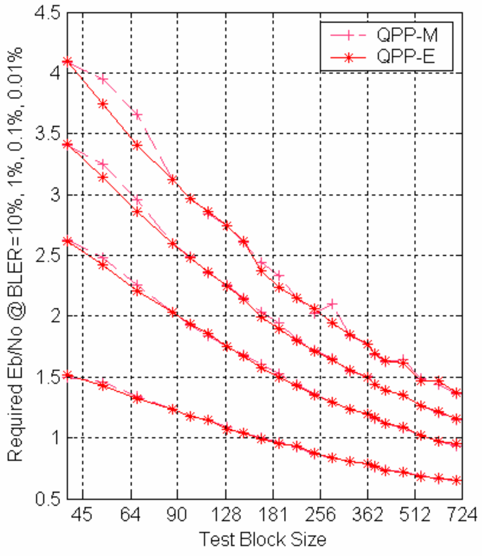

nInfoBits K=7195
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
E_b/N_0 [dB]
PIL reference
QPP-E, $57x+226x^2$ mod 7232
QPP-M, $137x+456x^2$ mod 7296
QPP-Q, $71x+150x^2$ mod 7200
ARP-M, S=7296
ARP-B, S=7200
IBP, S=7296
QC, S=7200
LRI

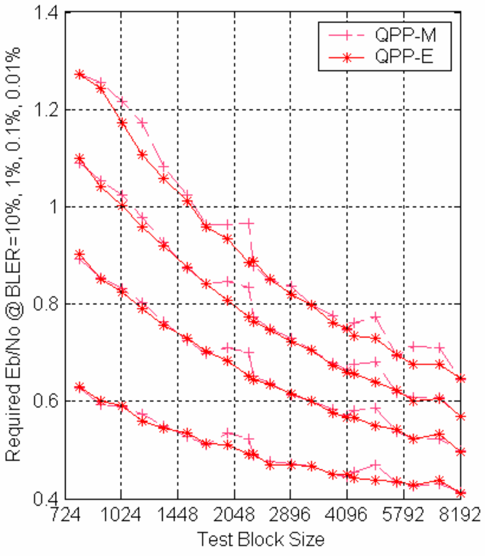

nInfoBits K=8192
Block Error Rates
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
E_b/N_0 [dB]
PIL reference
QPP-E, $33x+64x^2$ mod 8192
QPP-M, $417x+448x^2$ mod 8192
QPP-Q, $13x+128x^2$ mod 8192
ARP-M, S=8192
ARP-B, S=8200
IBP, S=8192
QC, S=8192
LRI

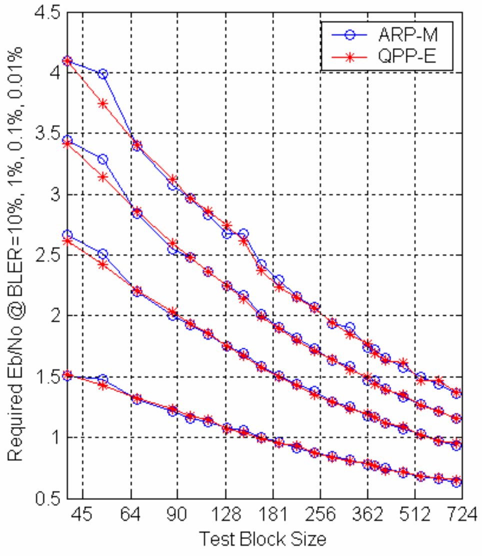
Appendix B — Pair-wise Performance Comparison

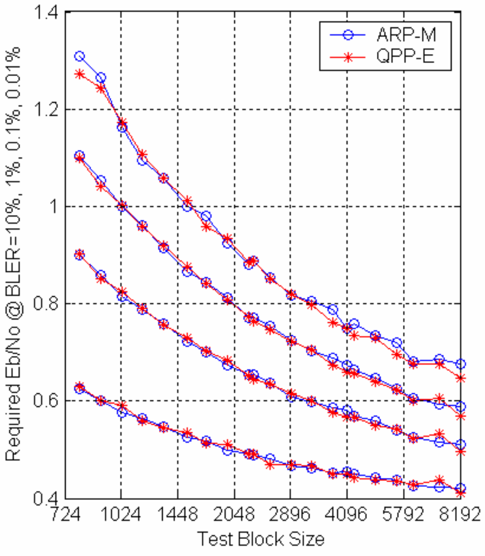


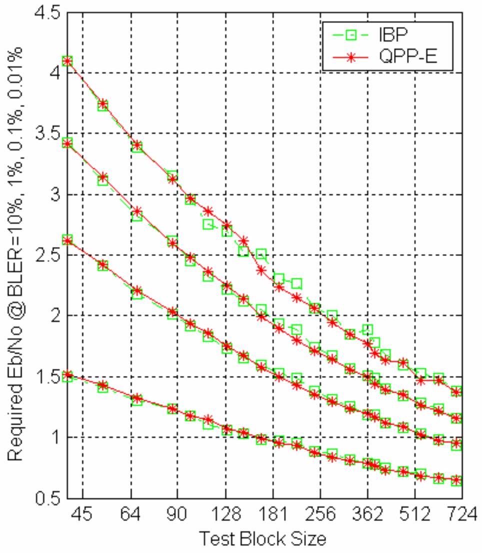


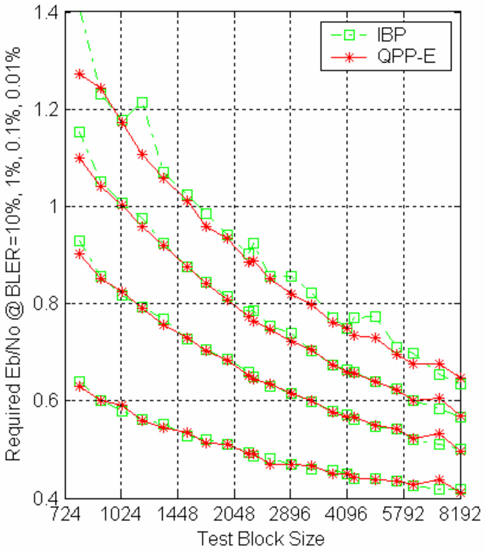


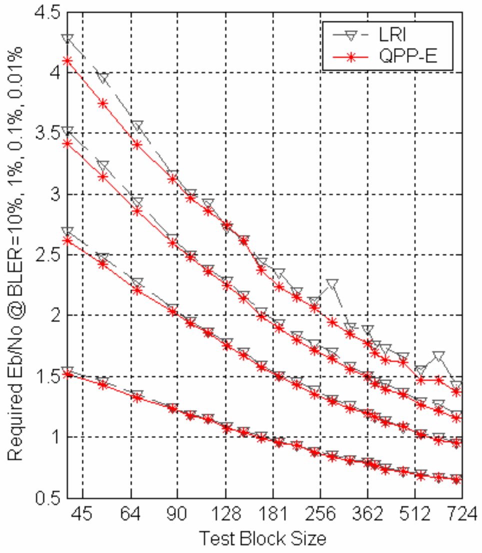


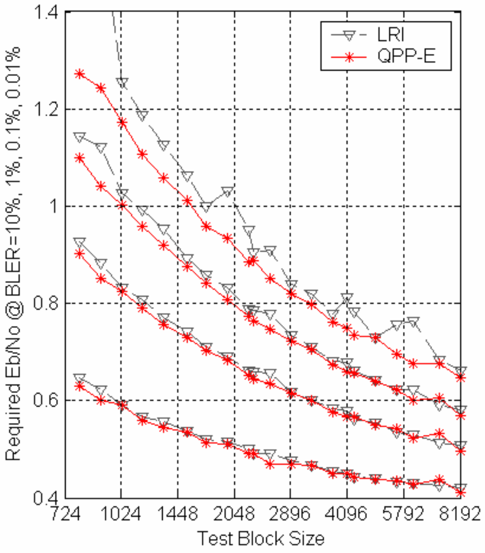


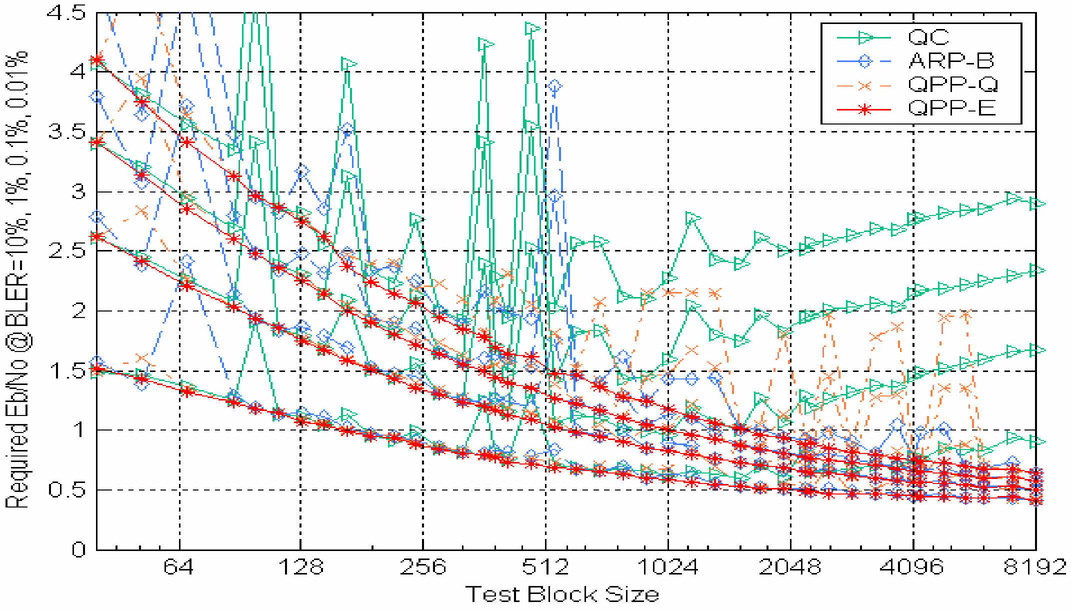



IBP
QPP-E
Required Eb/No @ BLER=10%, 1%, 0.1%, 0.01%
4.5
4
3.5
3
2.5
2
1.5
1
0.5
45
64
90
128
181
256
362
512
724
Test Block Size


IBP
QPP-E
Required Eb/No @ BLER=10%, 1%, 0.1%, 0.01%
1.4
1.2
1
0.8
0.6
0.4
724
1024
1448
2048
2896
4096
5792
8192
Test Block Size


LRI
QPP-E
Required Eb/No @ BLER=10%, 1%, 0.1%, 0.01%
4.5
4
3.5
3
2.5
2
1.5
1
0.5
45
64
90
128
181
256
362
512
724
Test Block Size


LRI
QPP-E
Required Eb/No @ BLER=10%, 1%, 0.1%, 0.01%
1.4
1.2
1
0.8
0.6
0.4
724
1024
1448
2048
2896
4096
5792
8192
Test Block Size


QC
ARP-B
QPP-Q
QPP-E
Required Eb/No @ BLER=10%, 1%, 0.1%, 0.01%
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
64
128
256
512
1024
2048
4096
8192
Test Block Size