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Purpose: [To be considered in IEEE 802.15.6]

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Introduction

Implant Device Communications in MICS Band

- 402 - 405 MHz, Maximum 300 KHz channel spacing (@-20dB).
- Maximum transmission power 25 uW (EIRP).
- Three communication scenarios:

  S1: Implant to Implant

  S2: Implant to Body Surface

  S3: Implant to External
- Communication Range of 50 ~ 500 mm (S1 & S2).

PHY Solution for Implant Communications

- **Modulation Method**: **Minimum Shift Keying ((G)MSK)**
  - A high bandwidth-efficient modulation scheme.
  - Retaining reasonable power efficiency and implementation complexity.
  - GMSK as an option for reduction of adjacent channel interference.
  - Matured technology.

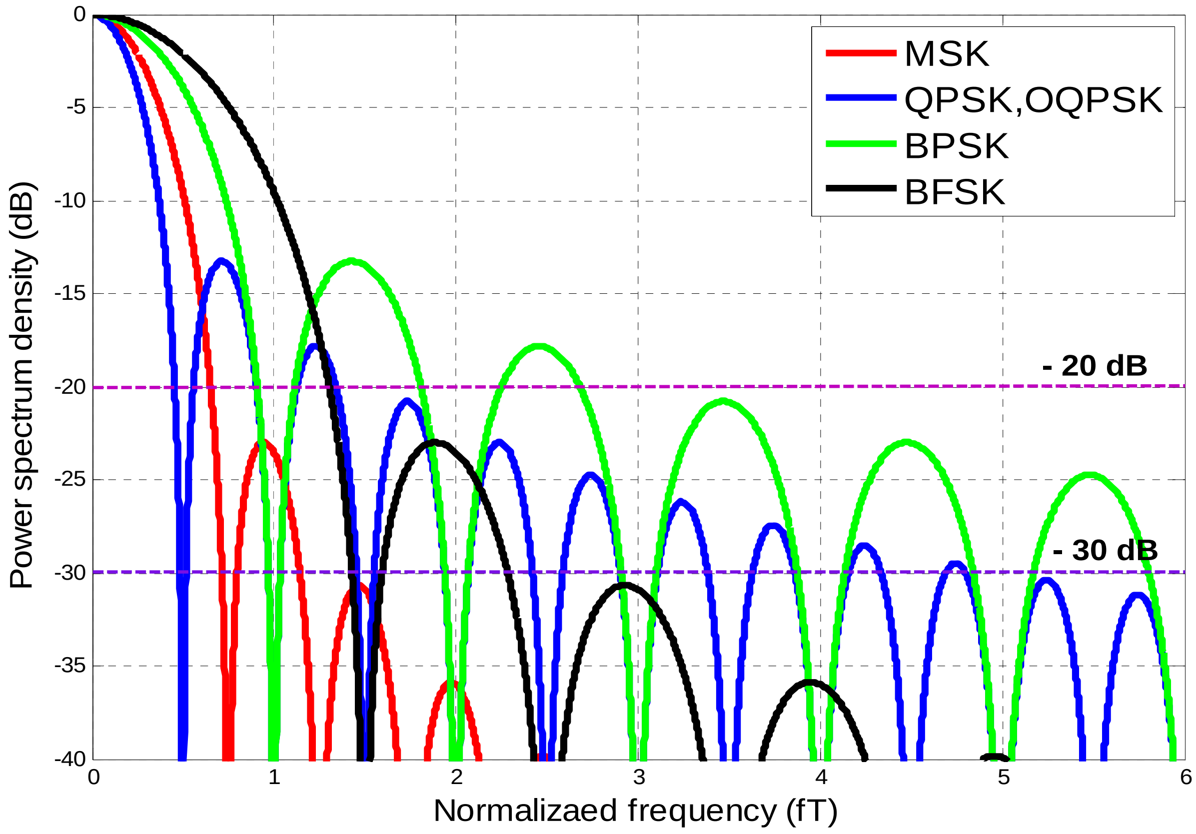
- **Error Correction Methods:**

  Binary Convolution Code, **Reed-Solomon Code**, **QC-LDPC**
  - Flexible FEC schemes:
    code type, code length, code rate.
  - **Unequal Error Protection** to the most significant information bits.
  - Complexity vs. System Performance.
  - Significant coding gain achieved for alleviating the rigor in receiver.

Modulation Method: Features of (G)MSK

- ✓ Continuous-phase frequency-shift keying
- ✓ Constant-modulus signal (insensitive to non-linear distortion)
- ✓ High spectrum efficiency
- ✓ Lower spectral side lobes than BFSK, QPSK, BPSK
- ✓ Smaller interference to adjacent channels
- ✓ Same bit error probability with BPSK
- ✓ Higher bandwidth efficiency than QPSK, BPSK (@20dB BW)
- ✓ Easy-to-implement I/Q modulation

Systematic Comparisons (1): Spectrum



Power spectrum densities of modulation schemes.

Note: BFSK with modulation index h=0.5, discrete component at fT=0.5 not displayed.

Systematic Comparisons (2): Bandwidth Efficiency

Table 1. Bandwidth-efficiencies of possible candidate modulation schemes in MICS band.

MOD. / BW Def.	MSK	2FSK*	OOK/BPSK	QPSK/OQPSK
Nyquist BW	2	1	1	2
20dB BW	0.767	0.384	0.186	0.372
Null-to-Null BW	0.667	0.333	0.5	1
30dB BW	0.438	0.352	0.052	0.104

In the bandwidth-efficiency plane,

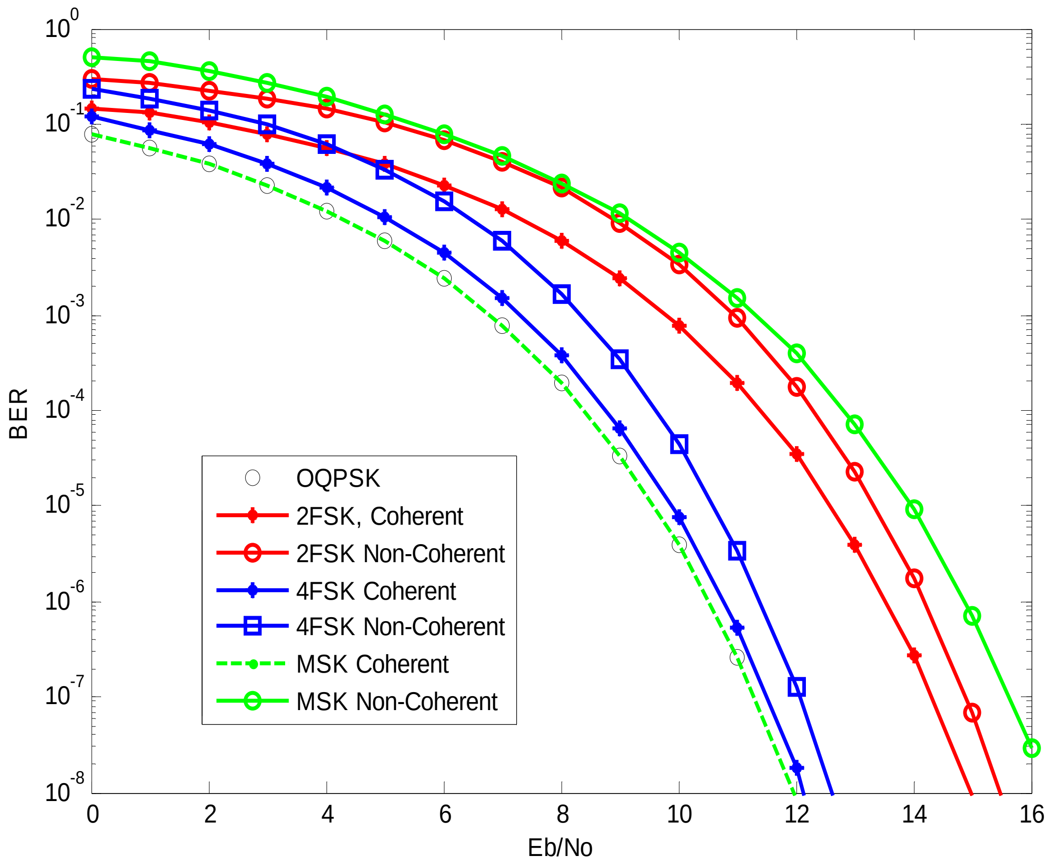
- Bandwidth efficiency is traded off against power efficiency.
- FSK is power efficient, but not bandwidth efficient.
- MSK is more bandwidth-efficient than QPSK for 20dB BW.
- Implant communications are bandwidth limited, therefore MSK is more suited for higher data rates in MICS band.

$$\eta = \frac{R}{W} \left(\frac{\text{bits/s}}{\text{Hz}} \right)$$

R: the data rate (bps)
W: bandwidth occupied by the modulated RF signal

* Coherent demodulation, modulation index h=0.5

Systematic Comparisons (3): BER



Theoretical BER performance of possible candidate modulation schemes in MICS band.

In the error probability plane,

- Theoretical BER performances of OQPSK, QPSK, BPSK, and MSK are identical.
- BER performance of 2FSK is about 3dB worse than that of MSK.
- Non-coherent demodulation is not suitable for MSK in MICS band communication.

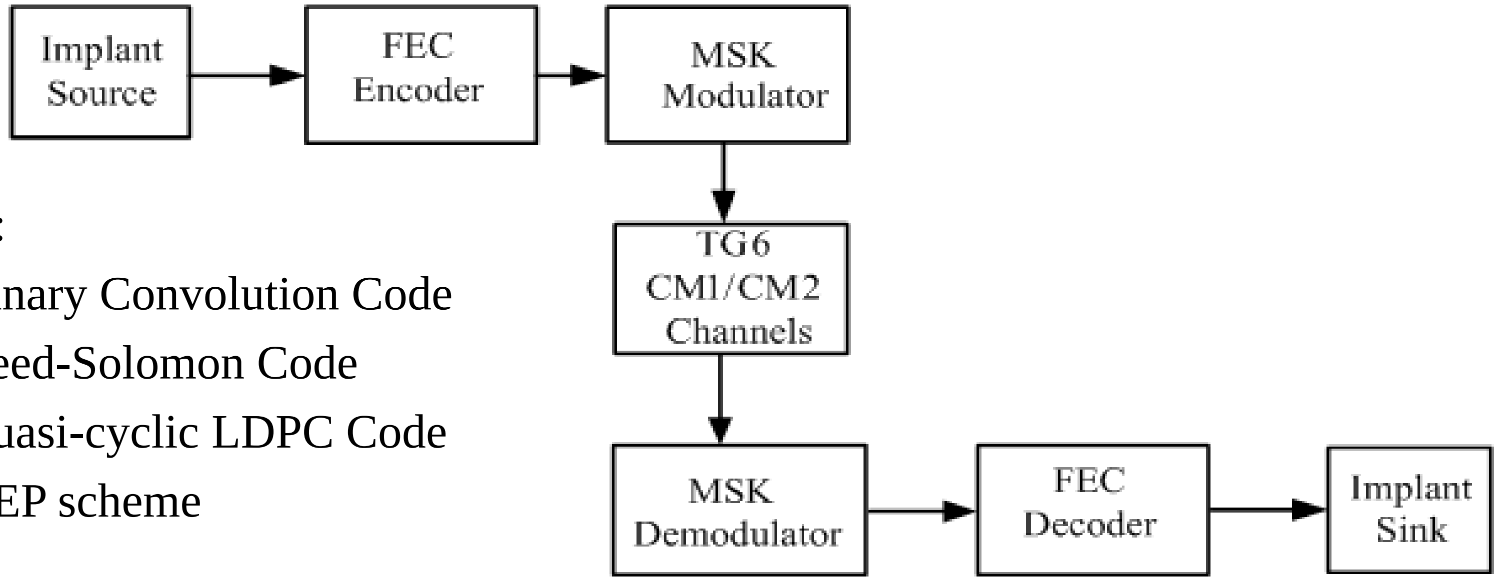
Systematic Comparisons (4)

Table 2. Systematic comparisons among possible candidate modulation schemes in MICS band.

	MSK	FSK	PSK
Nonlinear Amp.	OK	OK	NG
Detection	Coherent	Coherent/Non-coherent	Coherent
Bandwidth Effcy.	Good	NG	Best
BER	Good	Worse than MSK	Good

- FSK cannot support a high data rate for implant device communication, due to much lower bandwidth-efficiency;
- PSK is subject to nonlinear amplifier effects and gives larger inter-channel interference;
- MSK possesses advantages in bandwidth efficiency, small side lobe, and satisfactory BER performance.

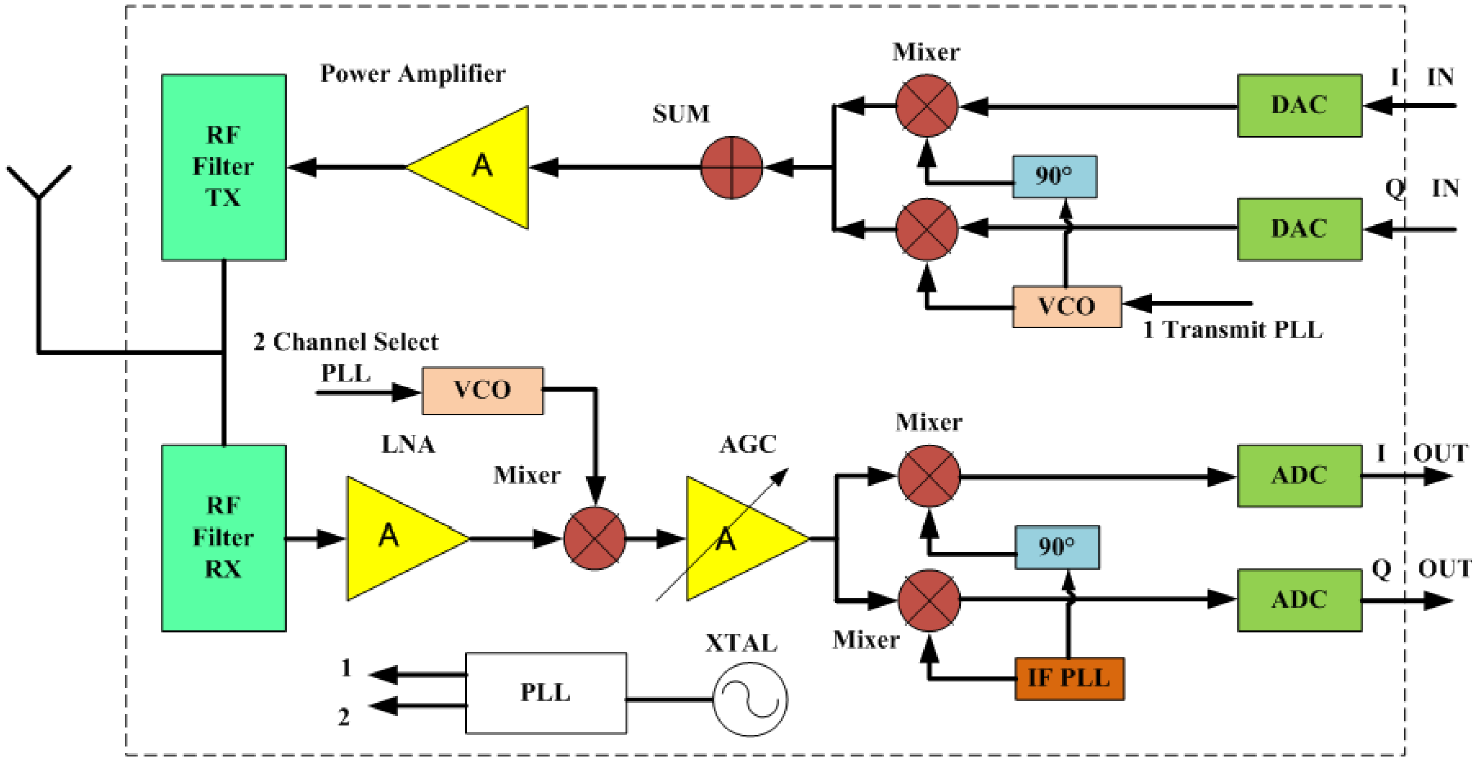
System Block Diagram



- FEC:
  - ✓ Binary Convolution Code
  - ✓ Reed-Solomon Code
  - ✓ Quasi-cyclic LDPC Code
  - ✓ UEP scheme
- Modulation:
  - ✓ (G)MSK
  - ✓ Null-to-Null Bandwidth
- Channels and communication scenarios
  - ✓ Path-loss
  - ✓ Log-normal shadowing

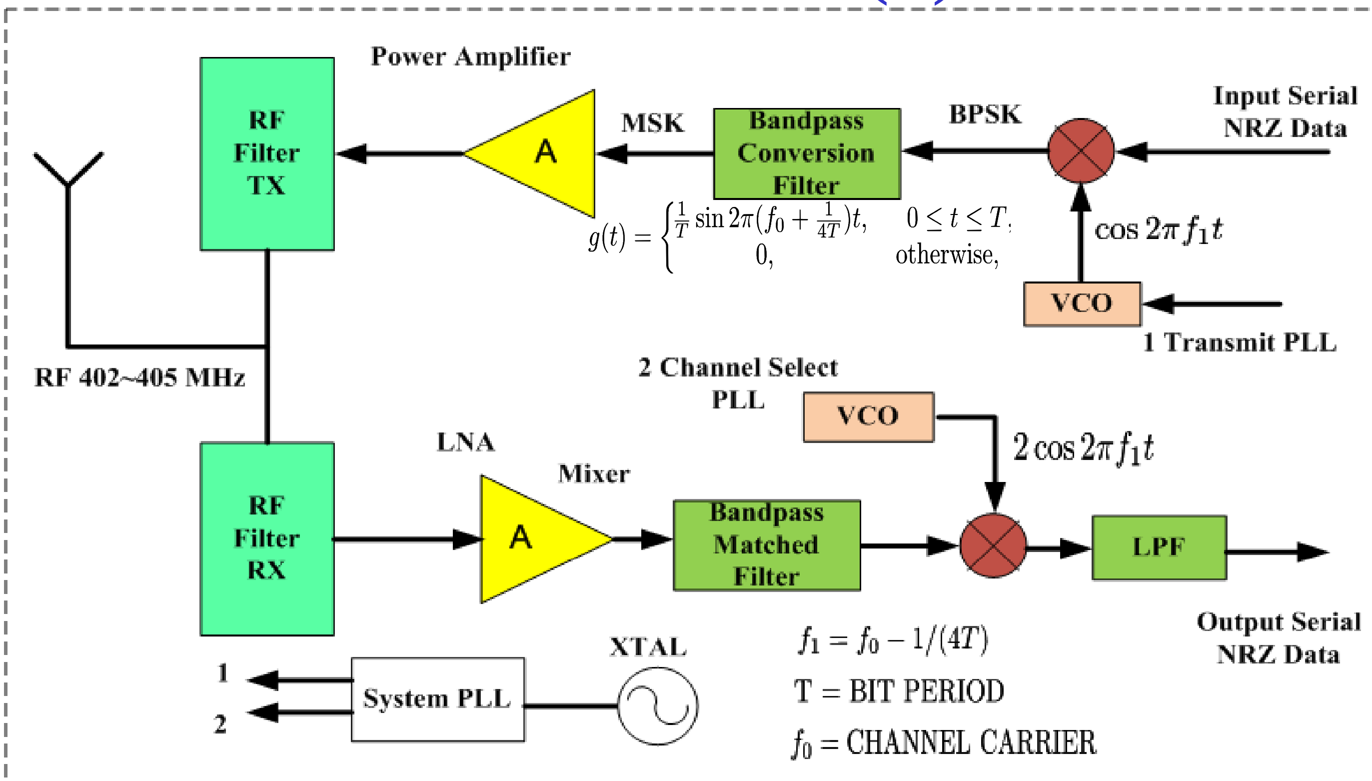
Scenario	Description	Frequency Band	Channel Model
S1	Implant to Implant	402-405 MHz	CM1
S2	Implant to Body Surface	402-405 MHz	CM2
S3	Implant to External	402-405 MHz	CM2

Transceiver Architecture (1): Parallel MSK



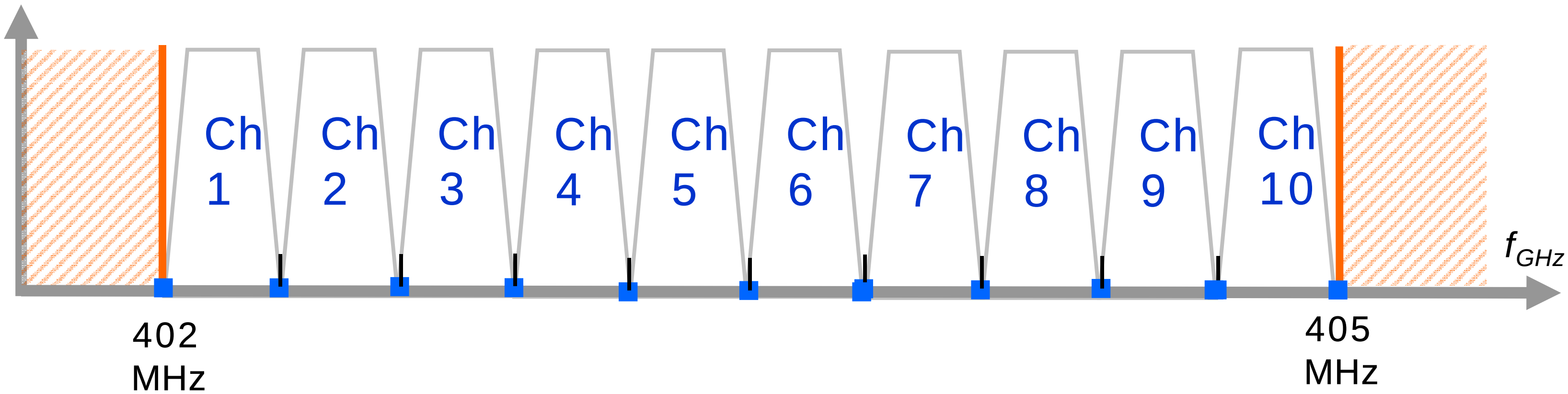
- In-phase/Quadrature-phase (I-Q) MSK modulation/demodulation
- Tx/Rx RF 402~405MHz
- 10 channels with channel spacing 300KHz

Transceiver Architecture (2): Serial MSK



- Quadrature-multiplexed modulation → serial modulation
- BER performance of Serial MSK is identical to Parallel MSK.
- The precise synchronization and balancing required for the quadrature signals of the parallel structures are no longer required.
- The sensitivity of the Serial MSK modulator and demodulator to amplitude and phase balance is reduced significantly from the requirements of the parallel MSK.

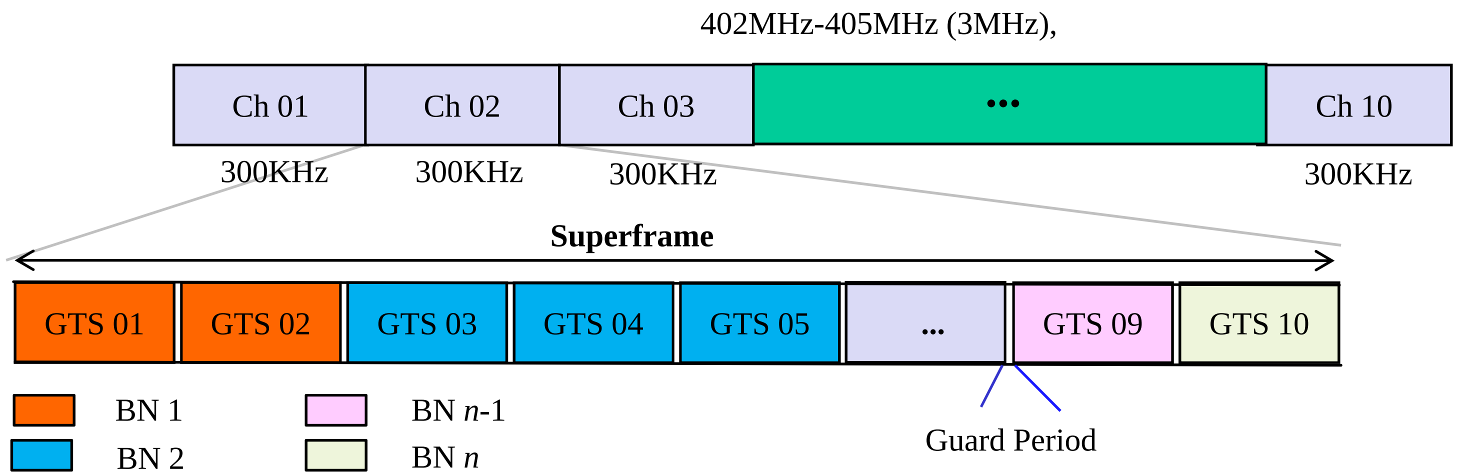
Channelization



- Channel separation: 300 KHz.
- Same XTAL support and PLL architecture as full-rate channelization.
- Null-to-Null bandwidth offers up to 200 kbps data rate.
- Nyquist bandwidth provides up to 600 kbps data rate.

	100 KHz	200 KHz	300 KHz
Null-to-Null BW	67 Kbps	133 Kbps	200 Kbps
20dB BW	77 Kbps	154 Kbps	231 Kbps
Nyquist BW	200 Kbps	400 Kbps	600 Kbps

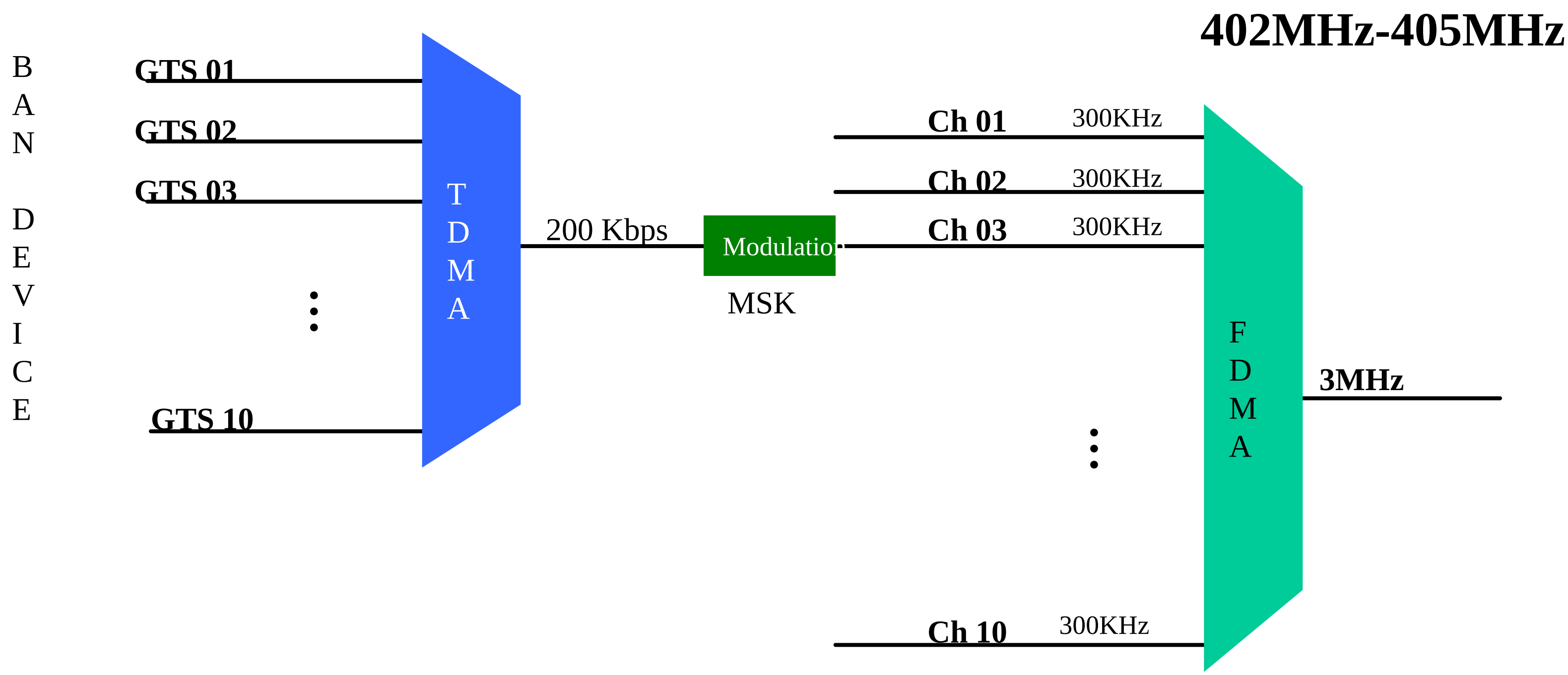
Multiple-Access Method: FDMA/TDMA



Step 1: Each BN is allocated a unique channel by BNC.

Step 2: A total of 10 guaranteed time slot (GTS) can be allocated to multiple BNs. During the communication period of one BN, no other BN can share the same frequency band.

Multiple-Access Method: FDMA/TDMA



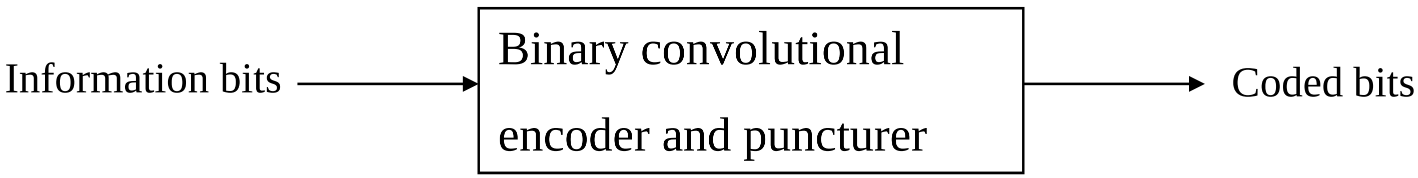
- ✓ Centralized and guaranteed time-frequency resource allocation.
- ✓ Free of user contention.
- ✓ Capable of maximum spectrum utilization.
- ✓ Adjustable data rate from low to medium.

Error Correcting Schemes

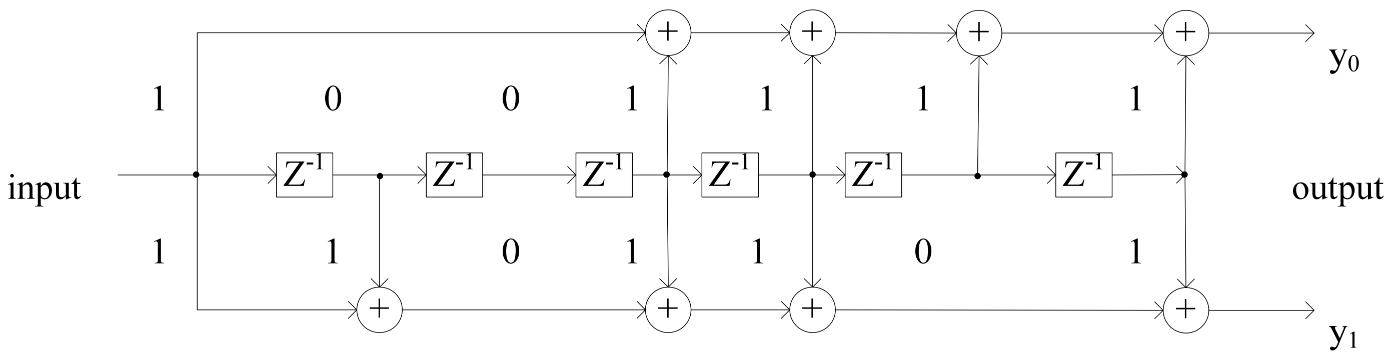
- FEC Options:
  1. Binary Convolutional Code (BCC).
  2. Systematic Reed-Solomon Code (RS).
  3. Quasi-cyclic LDPC Code (QC-LDPC).

- UEP Options:
  1. BCC/RS/QC-LDPC offers protection for MSB only.
  2. QC-LDPC and BCC cooperate for protecting MSB and LSB, respectively.

FEC option 1: Binary Convolutional Code

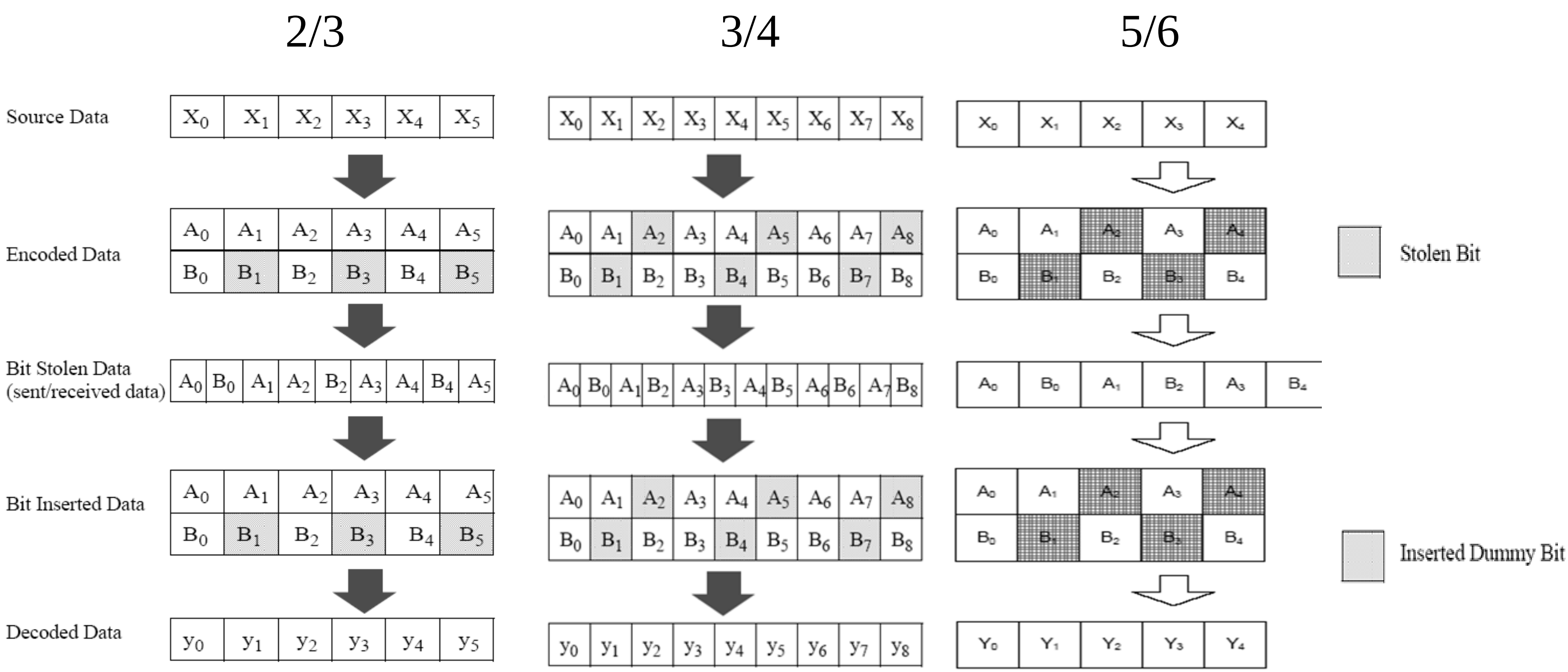


- Convolutional encoder Code rate: 1/2 Constraint length: 7
- Generator polynomial $g0=171_8$, $g1=133_8$



BCC Encoder Diagram

Puncture patterns for BCC

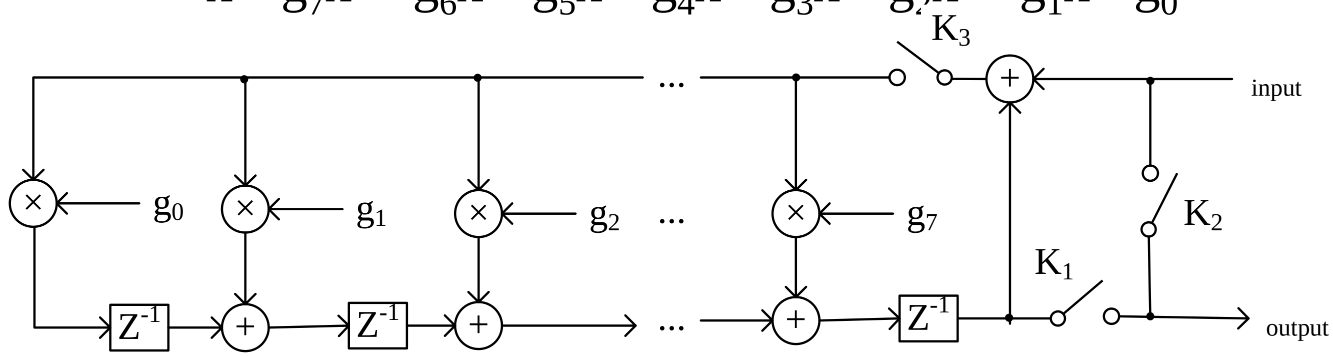


FEC option 2: Reed-Solomon Code

- Systematic RS code 1 : n=31, k=23, t=4
- Generator polynomial

$$g(x) = x^8+8x^7+ 21x^6+15x^5+6x^4+2x^3+26x^2+ 18x +5$$

$$= x^8+g_7x^7+ g_6x^6+g_5x^5+g_4x^4+g_3x^3+g_2x^2+ g_1x +g_0$$



RS Encoder Diagram 1

- Encoding operation:

Step 1. Reset shift register to all zeros.

Step 2. Switches K_2, K_3 are on, K_1 is off. The k information bytes are fed into the encoder.

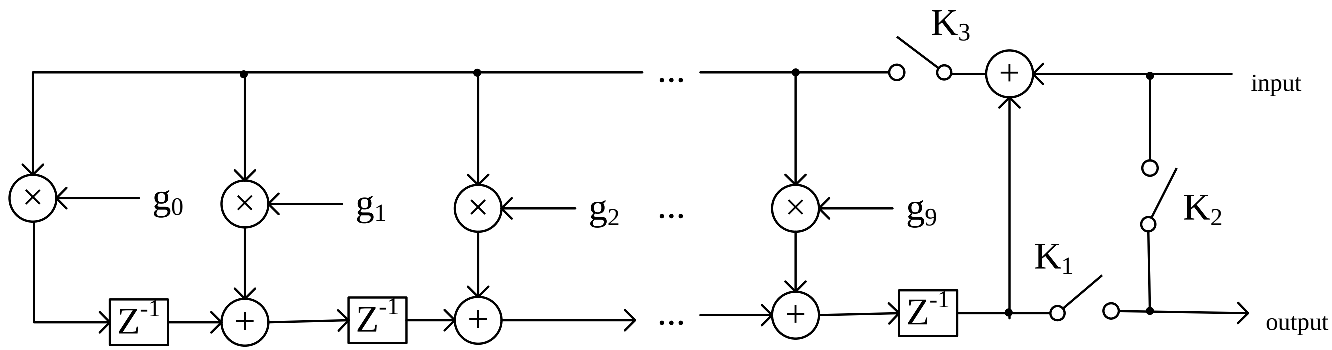
Step 3. After the last byte has been fed into the shift register, Switches K_2, K_3 are off , K_1 is on.

The n-k parity-check bytes are calculated and output.

- Systematic RS code 2 : n=63, k=53, t=5
- Generator polynomial

$$g(x) = x^{10}+31x^9+28x^8+39x^7+ 42x^6+57x^5+2x^4+3x^3+49x^2+ 44x +46$$

$$= x^{10}+g_9x^9+g_8x^8+g_7x^7+ g_6x^6+g_5x^5+g_4x^4+g_3x^3+g_2x^2+ g_1x +g_0$$



RS Encoder Diagram 2

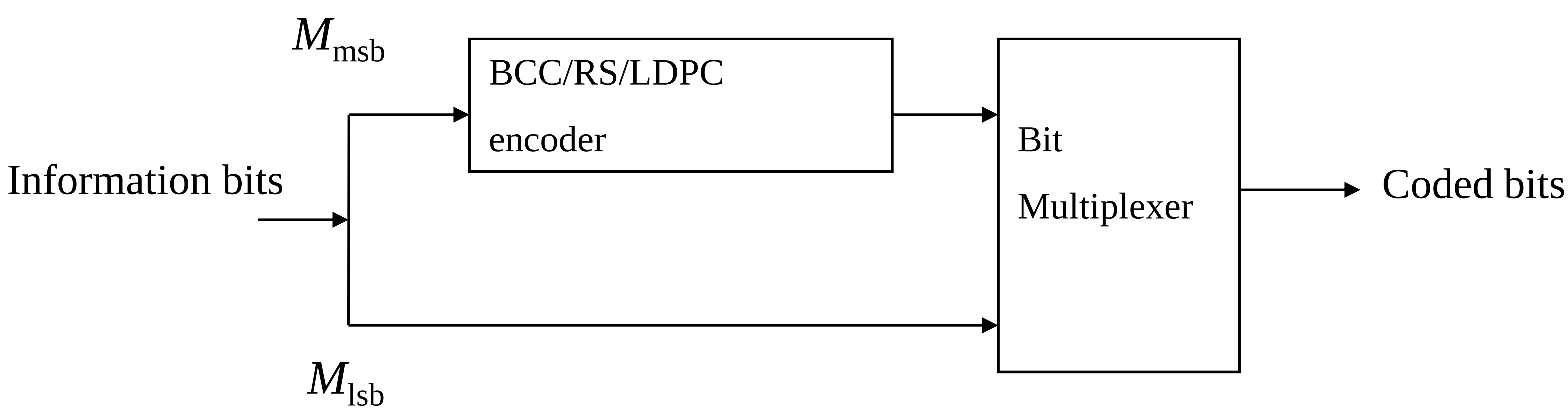
FEC option 3: Quasi-cyclic LDPC Code

- Low complexity systematic encoder
- Low complexity high parallel decoder
- Potential of high throughput encoder and decoder
- Supports code length 672 and 1008
- Supports code rates 1/2, 2/3, 3/4, and 5/6

Number of bits in a codeword	Number of information bits in a codeword	Number of parity-check bits in a codeword	Code rate	Dimension of the submatrix
672	336	336	1/2	28
672	448	224	2/3	28
672	504	168	3/4	28
672	560	112	5/6	28
1008	504	504	1/2	28
1008	672	336	2/3	28
1008	756	252	3/4	28
1008	840	168	5/6	28

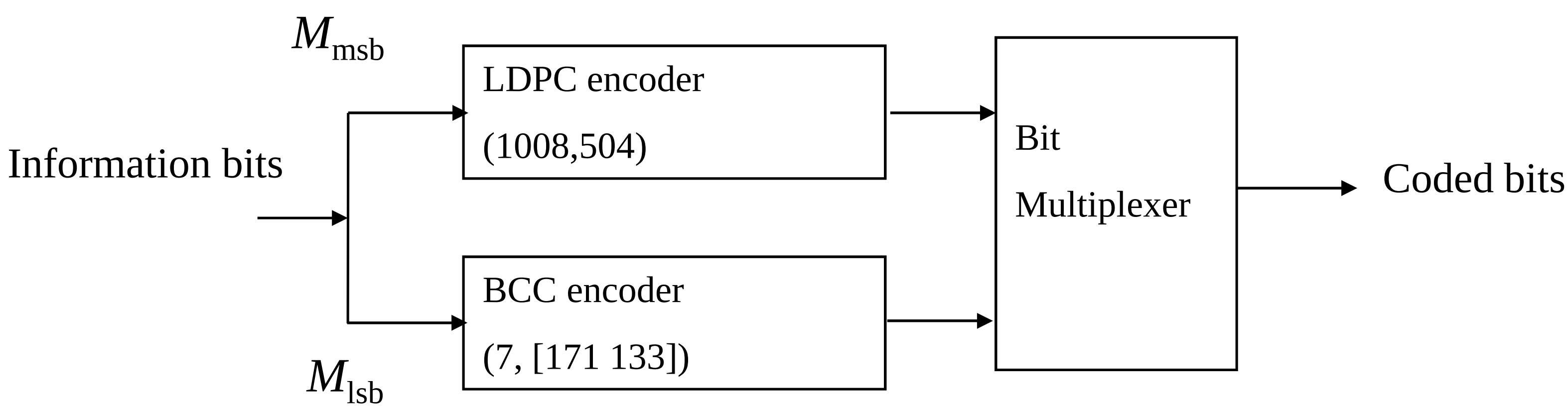
UEP option 1

- Most significant bits are encoded with BCC/RS/LDPC codes.
- Least significant bits are not encoded.



UEP option 2

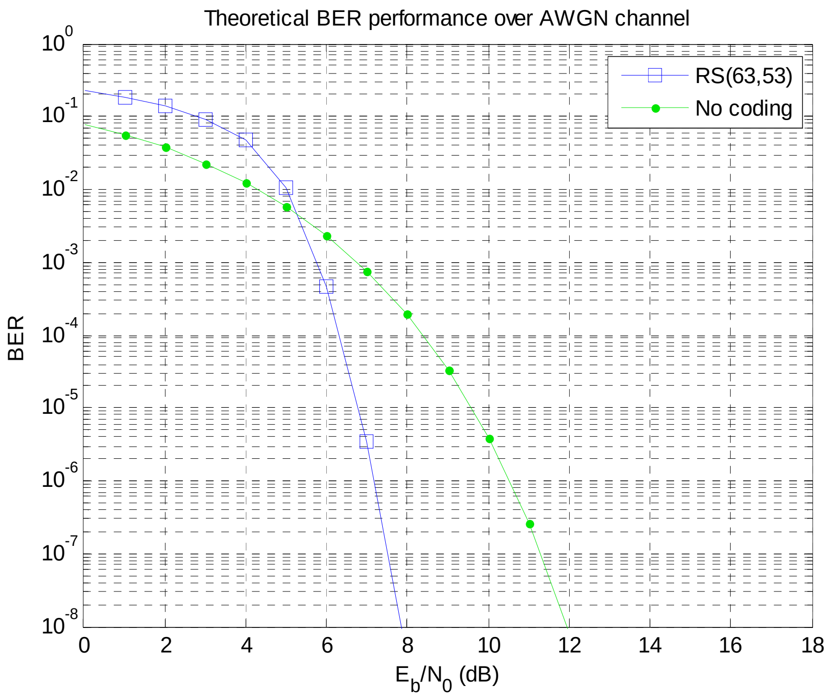
- Most significant bits are encoded with LDPC (1008,504).
- Least significant bits are encoded with BCC (7, [171 133]).



Link Budgets

	Parameters	Value	Value	Value	units
1	Center Frequency	403.5	403.5	403.5	MHz
2	Transmission bandwidth (Nyquist bandwidth)	3	0.3	0.1	MHz
3	Transmission power	-16	-16	-16	dBm
4	Tx Antenna Gain	0	0	0	dBi
5	Rx Antenna Gain	0	0	0	dBi
6	Path Loss @ 2cm (Implant to body surface, CM2 Channel)	33.0	33.0	33.0	dB
7	Add. Path Loss @ 3m (From body surface, free space)	34.1	34.1	34.1	dB
8	Log-normal fading margin	6.8	6.8	6.8	dB
9	Received power @ 3 m	-89.9	-89.9	-89.9	dBm
10	Thermal noise density	-174	-174	-174	dBm/Hz
11	Receiver noise figure	10	10	10	dB
12	Receiver noise power density	-164	-164	-164	dBm/Hz
13	Receiver noise power	-99	-109	-114	dBm
14	Link margin	10.0	10.0	10.0	dB
15	Required Eb/N0 @ BER=1.35×10-5 (LDPC[672,336])	3.2	3.2	3.2	dB
16	Required Eb/N0 @ BER=1.05×10-5 (BCC[7,(171,133)])	6.5	6.5	6.5	dB
17	Required Eb/N0 @ BER=1.05×10-5 (RS[31,23])	7.0	7.0	7.0	dB
18	Receiver sensitivity with LDPC code [672,336]	-85.7	-95.7	-100.5	dBm
19	Receiver sensitivity with BCC code [7,(171,133)]	-82.4	-92.4	-97.2	dBm
20	Receiver sensitivity with RS Code [31,23]	-81.9	-91.9	-96.7	dBm

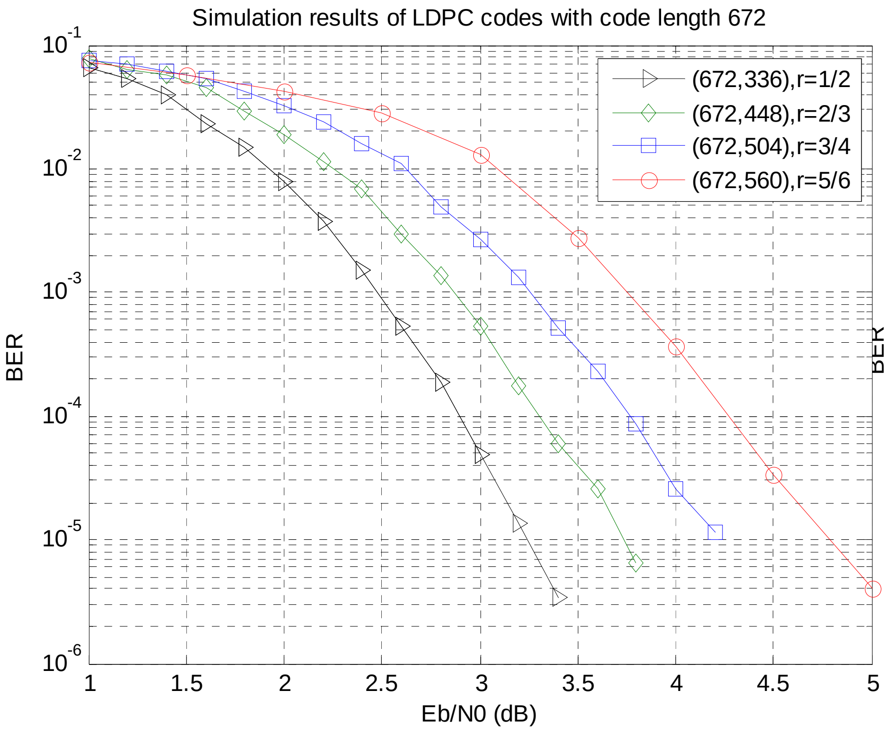
Performance Evaluation (1): BER



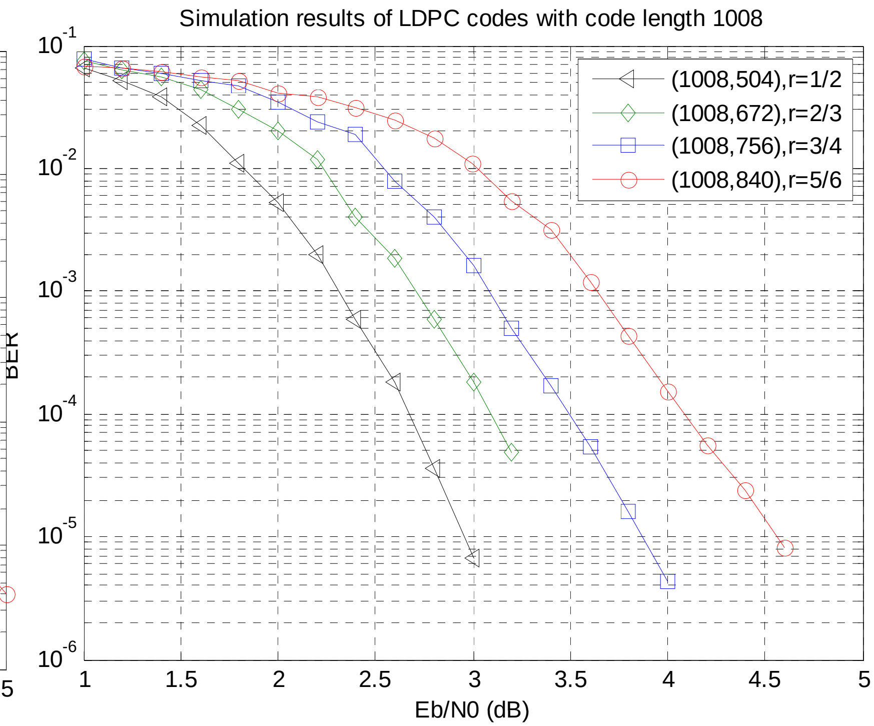
RS Code (63, 53)

- RS code helps in improving BER performance only when a certain Eb/No is guaranteed.
- An approximate coding gain of 3.2 dB can be achieved at BER 10^{-6} .

Performance Evaluation (2): BER



LDPC with code word length 672, 10 iterations

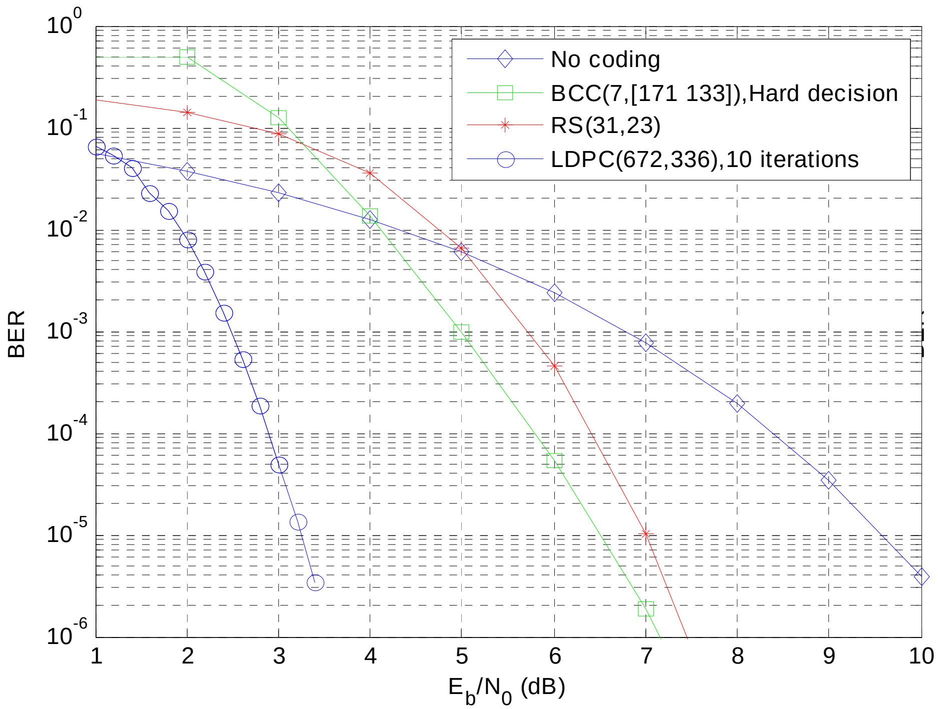


LDPC with code word length 1008,10 iterations

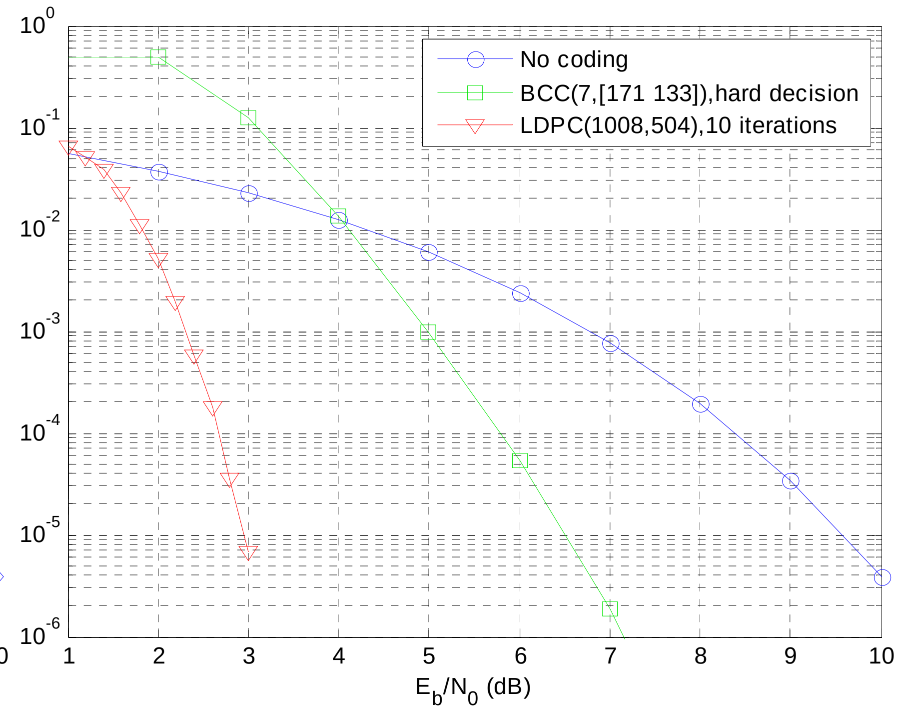
LDPC

- Different coding rates contribute to different improvement in BER performance.
- Longer code length yields better BER performance.

Performance Evaluation (3): BER



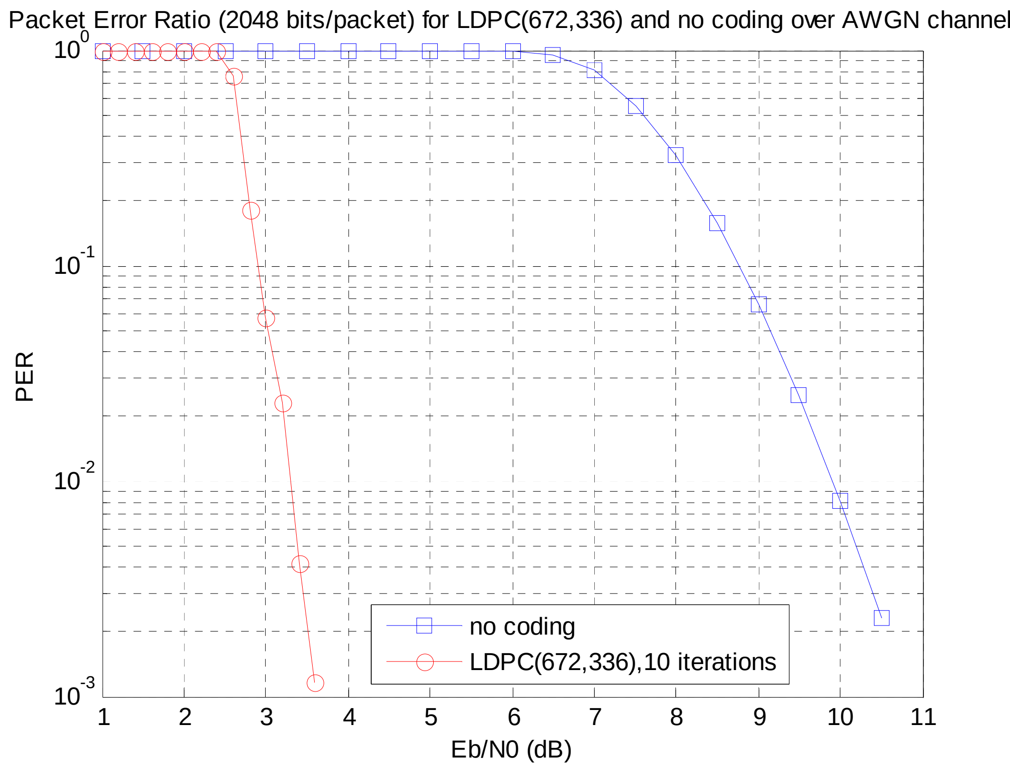
UEP with BCC/RS/QC-LDPC



UEP with QC-LDPC and BCC

- The MSB information bits are given sufficient error protection even at low Eb/No.
- BCC can provide better error correction for the LSB information bits than RS.

Performance Evaluation (4): PER



- Packet Error Ratio comparison.
- 256 octets per packet.
- PER 10^{-2} approximately corresponds to BER 10^{-5}.

Summary

- A simple and bandwidth-efficient PHY scheme based on MSK is proposed as a narrowband PHY solution operable in MICS bands.
- A flexible error correction scheme based on BCC/RS/QC-LDPC codes is proposed to substantially enhance the system BER performance under CM1 and CM2 channels.
- Two UEP strategies are proposed to provide different error corrections for MSB and LSB.
- The whole solution is based on matured modulation and channel coding techniques.

Appendix I.: Code Design

- Parity-check matrix for LDPC(672,336)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	-1	20	-1	-1	-1	-1	22	-1	0	0	-1	-1	-1	0	-1	-1	-1	-1	-1	-1	-1	-1	27	-1
2	-1	-1	-1	10	-1	-1	-1	22	10	-1	-1	-1	2	-1	-1	-1	-1	-1	3	-1	-1	-1	11	-1
3	-1	-1	-1	4	-1	-1	-1	23	27	-1	-1	-1	-1	-1	-1	-1	24	10	-1	-1	7	-1	-1	-1
4	20	-1	-1	-1	-1	17	-1	-1	-1	-1	1	-1	-1	-1	-1	5	-1	24	-1	-1	-1	-1	-1	18
5	-1	11	-1	-1	12	-1	-1	-1	-1	-1	-1	27	-1	-1	15	-1	5	-1	-1	8	-1	-1	-1	-1
6	-1	-1	-1	24	-1	18	-1	-1	-1	-1	-1	-1	25	-1	-1	17	24	-1	-1	-1	25	-1	-1	-1
7	-1	-1	16	-1	4	-1	-1	-1	-1	7	-1	-1	-1	-1	-1	4	-1	-1	22	-1	-1	4	-1	-1
8	-1	-1	17	-1	-1	-1	-1	12	-1	-1	5	-1	-1	10	-1	-1	-1	-1	-1	14	-1	-1	4	-1
9	-1	16	-1	-1	-1	-1	12	-1	-1	-1	-1	-1	27	-1	4	-1	-1	-1	25	-1	-1	2	-1	-1
10	12	-1	-1	-1	-1	27	-1	-1	-1	-1	9	18	-1	-1	-1	-1	-1	-1	-1	-1	20	-1	-1	1
11	20	-1	-1	-1	-1	-1	21	-1	-1	-1	-1	15	-1	-1	0	-1	-1	-1	-1	23	-1	-1	-1	10
12	-1	-1	26	-1	7	-1	-1	-1	-1	19	-1	-1	-1	22	-1	-1	-1	13	-1	-1	-1	24	-1	-1

- Parity-check matrix for LDPC(672,560)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	-1	0	8	0	0	-1	-1	16	-1	4	-1	6	9	19	7	-1	7	-1	6	21	24	15	-1	14
2	26	1	-1	23	-1	3	22	23	21	-1	24	6	1	-1	16	22	-1	2	2	12	23	8	16	-1
3	10	-1	24	9	22	14	20	-1	13	-1	27	3	-1	3	21	12	18	8	26	-1	14	-1	20	1
4	19	12	-1	-1	15	1	25	1	15	23	12	-1	10	11	-1	2	6	22	-1	24	-1	5	2	20

Appendix II.

- Parity-check matrix for LDPC(672,448)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	-1	24	-1	-1	10	0	-1	0	-1	-1	-1	0	-1	-1	-1	-1	15	-1	-1	2	-1	-1	-1	10
2	-1	-1	9	-1	-1	0	6	-1	-1	2	-1	23	-1	-1	21	-1	-1	-1	4	-1	5	0	-1	-1
3	23	-1	-1	0	-1	-1	-1	15	19	-1	-1	-1	25	-1	-1	-1	6	2	-1	-1	6	2	-1	-1
4	-1	20	-1	-1	20	-1	10	-1	-1	-1	11	-1	-1	24	-1	15	-1	0	22	-1	-1	-1	-1	12
5	-1	-1	24	-1	18	-1	6	-1	-1	-1	18	5	-1	-1	25	17	-1	-1	-1	9	-1	-1	4	-1
6	1	-1	-1	0	-1	-1	-1	22	-1	20	-1	-1	-1	14	-1	10	-1	-1	16	-1	1	-1	-1	16
7	15	-1	10	-1	-1	-1	-1	-1	16	2	-1	-1	19	-1	13	-1	14	-1	-1	7	-1	-1	12	-1
8	-1	19	-1	18	-1	-1	-1	-1	1	-1	9	-1	11	6	-1	-1	-1	11	-1	-1	-1	24	21	-1

- Parity-check matrix for LDPC(672,504)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	-1	26	-1	15	0	-1	-1	-1	-1	1	-1	17	-1	21	6	-1	-1	-1	12	0	-1	-1	2	-1
2	10	-1	-1	-1	7	26	-1	16	14	-1	7	-1	-1	5	20	-1	27	-1	-1	27	-1	20	-1	4
3	-1	10	-1	24	-1	-1	3	9	17	-1	16	-1	27	-1	24	-1	-1	21	-1	-1	21	27	12	-1
4	-1	7	16	-1	1	-1	26	-1	5	-1	20	-1	-1	10	-1	19	-1	7	-1	23	-1	26	-1	27

Appendix III.

- Parity-check matrix for LDPC(1008,504)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	-1	14	-1	-1	-1	-1	9	-1	-1	-1	-1	0	-1	-1	-1	-1	-1	-1	6	-1	-1	-1	-1	-1	-1	-1	-1	26	0	-1	-1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	-1	5	-1	-1	27	-1	-1	-1	-1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	20	13	-1	-1	-1	-1	-1	-1	-1	-1	-1	4	-1
3	-1	-1	-1	-1	5	-1	-1	4	-1	-1	-1	-1	13	-1	-1	-1	-1	-1	-1	-1	1	-1	-1	-1	-1	-1	12	-1	-1	-1	-1	17	-1	-1	-1	-1
4	-1	-1	-1	9	-1	-1	-1	-1	-1	-1	-1	27	-1	-1	-1	14	-1	-1	-1	-1	-1	-1	-1	27	-1	23	-1	-1	-1	-1	-1	-1	-1	-1	-1	16
5	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	27	-1	-1	-1	-1	26	21	-1	-1	-1	-1	-1	27	-1	-1	-1	-1	-1	21	-1	-1	-1	-1	24
6	-1	-1	-1	-1	-1	24	-1	-1	-1	-1	-1	13	-1	0	-1	-1	-1	-1	-1	-1	7	-1	-1	-1	-1	-1	-1	-1	-1	3	8	-1	-1	-1	-1	-1
7	-1	11	-1	-1	-1	-1	-1	-1	-1	-1	17	-1	-1	-1	-1	-1	-1	27	-1	-1	-1	-1	21	-1	-1	-1	-1	-1	-1	-1	1	-1	-1	-1	-1	-1
8	-1	-1	-1	-1	16	-1	-1	-1	-1	26	-1	-1	-1	-1	17	-1	-1	-1	-1	-1	-1	-1	11	-1	-1	-1	16	-1	-1	-1	-1	-1	-1	19	-1	-1
9	-1	-1	-1	-1	-1	8	-1	-1	-1	7	-1	-1	-1	13	-1	-1	-1	-1	-1	-1	-1	16	-1	-1	-1	-1	-1	7	-1	-1	-1	-1	0	-1	-1	-1
10	-1	-1	4	-1	-1	-1	-1	-1	20	-1	-1	-1	-1	-1	-1	-1	25	-1	-1	27	-1	-1	-1	-1	-1	-1	10	-1	-1	-1	-1	-1	23	-1	-1	-1
11	-1	-1	-1	16	-1	-1	-1	-1	-1	6	-1	-1	-1	-1	-1	-1	-1	21	-1	-1	-1	2	-1	-1	-1	22	-1	-1	-1	-1	-1	17	-1	-1	-1	-1
12	-1	-1	14	-1	-1	-1	-1	-1	-1	-1	19	-1	-1	-1	-1	8	-1	-1	-1	26	-1	-1	-1	-1	26	-1	-1	-1	-1	-1	-1	-1	-1	-1	14	-1
13	-1	-1	8	-1	-1	-1	-1	-1	-1	-1	1	-1	-1	-1	13	-1	-1	-1	-1	-1	-1	23	-1	-1	-1	-1	-1	-1	15	-1	-1	-1	-1	18	-1	-1
14	-1	25	-1	-1	-1	-1	23	-1	-1	-1	-1	-1	-1	-1	-1	12	-1	-1	-1	12	-1	-1	-1	-1	-1	-1	-1	-1	6	-1	-1	-1	-1	-1	22	-1
15	0	-1	-1	-1	-1	-1	3	-1	-1	-1	-1	-1	-1	-1	-1	-1	10	-1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	15	-1	-1	-1	-1	-1	18
16	0	-1	-1	-1	-1	-1	-1	6	-1	-1	-1	-1	7	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	10	-1	27	-1	-1	-1	-1	-1	17	-1	-1	-1	-1
17	-1	-1	-1	-1	4	-1	-1	6	-1	-1	-1	-1	-1	-1	-1	-1	13	-1	-1	-1	-1	-1	16	-1	-1	-1	-1	0	-1	-1	-1	-1	23	-1	-1	-1
18	-1	-1	-1	25	-1	-1	-1	-1	27	-1	-1	-1	-1	-1	10	-1	-1	-1	-1	-1	20	-1	-1	-1	-1	-1	-1	-1	-1	14	-1	-1	-1	22	-1	-1

Appendix IV.

- Parity-check matrix for LDPC(1008,672)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	-1	20	-1	-1	-1	-1	22	-1	0	0	-1	-1	-1	0	-1	-1	-1	-1	-1	-1	-1	-1	27	-1	-1	4	-1	-1	-1	-1	3	-1	-1	-1	-1	13
2	-1	-1	-1	10	-1	-1	-1	22	10	-1	-1	-1	2	-1	-1	-1	-1	-1	3	-1	-1	-1	11	-1	-1	-1	10	-1	-1	-1	-1	1	-1	-1	-1	26
3	-1	-1	-1	4	-1	-1	-1	23	27	-1	-1	-1	-1	-1	-1	-1	24	10	-1	-1	7	-1	-1	-1	-1	-1	-1	14	-1	-1	21	-1	-1	2	-1	-1
4	20	-1	-1	-1	-1	17	-1	-1	-1	-1	1	-1	-1	-1	-1	5	-1	24	-1	-1	-1	-1	-1	18	-1	-1	-1	24	-1	14	-1	-1	4	-1	-1	-1
5	-1	11	-1	-1	12	-1	-1	-1	-1	-1	-1	27	-1	-1	15	-1	5	-1	-1	8	-1	-1	-1	-1	-1	26	-1	-1	-1	-1	-1	14	-1	9	-1	-1
6	-1	-1	-1	24	-1	18	-1	-1	-1	-1	-1	-1	25	-1	-1	17	24	-1	-1	-1	25	-1	-1	-1	-1	-1	7	-1	17	-1	-1	-1	-1	-1	-1	24
7	-1	-1	16	-1	4	-1	-1	-1	-1	7	-1	-1	-1	-1	-1	4	-1	-1	22	-1	-1	4	-1	-1	-1	27	-1	-1	-1	22	-1	-1	-1	-1	20	-1
8	-1	-1	17	-1	-1	-1	-1	12	-1	-1	5	-1	-1	10	-1	-1	-1	-1	-1	14	-1	-1	4	-1	19	-1	-1	-1	25	-1	-1	-1	-1	-1	1	-1
9	-1	16	-1	-1	-1	-1	12	-1	-1	-1	-1	-1	27	-1	4	-1	-1	-1	25	-1	-1	2	-1	-1	-1	-1	17	-1	-1	-1	-1	14	17	-1	-1	-1
10	12	-1	-1	-1	-1	27	-1	-1	-1	-1	9	18	-1	-1	-1	-1	-1	-1	-1	-1	20	-1	-1	1	18	-1	-1	-1	23	-1	-1	-1	-1	21	-1	-1
11	20	-1	-1	-1	-1	-1	21	-1	-1	-1	-1	15	-1	-1	0	-1	-1	-1	-1	23	-1	-1	-1	10	9	-1	-1	-1	-1	20	-1	-1	-1	-1	1	-1
12	-1	-1	26	-1	7	-1	-1	-1	-1	19	-1	-1	-1	22	-1	-1	-1	13	-1	-1	-1	24	-1	-1	-1	-1	-1	19	-1	-1	3	-1	19	-1	-1	-1

Appendix V.

- Parity-check matrix for LDPC(1008,756)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	-1	23	-1	-1	-1	23	0	-1	-1	0	0	-1	-1	6	-1	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	23	-1	-1	-1	10	-1	-1
2	-1	-1	7	-1	4	-1	-1	-1	19	-1	-1	-1	26	-1	22	-1	-1	-1	6	11	-1	-1	-1	-1	26	-1	17	-1	-1	-1	23	-1	10	-1	14	-1
3	15	-1	-1	0	-1	-1	-1	26	-1	-1	-1	13	-1	-1	9	-1	-1	-1	7	-1	-1	15	-1	12	-1	7	-1	-1	-1	22	-1	-1	9	0	-1	-1
4	-1	10	-1	-1	-1	24	-1	-1	-1	6	-1	-1	-1	14	-1	27	3	-1	-1	-1	-1	10	-1	11	-1	-1	-1	6	21	-1	-1	25	-1	-1	21	-1
5	-1	-1	8	-1	16	-1	-1	-1	0	-1	-1	1	-1	-1	-1	-1	19	-1	-1	5	10	-1	6	-1	-1	5	-1	16	-1	-1	-1	8	-1	-1	-1	16
6	-1	-1	18	-1	-1	-1	7	-1	9	-1	-1	24	-1	-1	-1	13	-1	10	-1	-1	2	-1	-1	-1	0	-1	16	-1	11	-1	15	-1	-1	-1	-1	10
7	6	-1	-1	16	-1	-1	-1	27	-1	-1	17	-1	-1	-1	-1	-1	17	11	-1	-1	22	-1	3	-1	-1	4	-1	23	-1	-1	-1	2	-1	-1	-1	21
8	0	-1	-1	-1	4	-1	-1	-1	-1	-1	17	-1	21	24	-1	-1	-1	25	-1	20	-1	-1	23	-1	-1	-1	2	-1	1	-1	14	-1	-1	2	-1	-1
9	-1	25	-1	25	-1	-1	-1	6	-1	-1	-1	-1	9	-1	18	-1	-1	-1	12	-1	-1	26	-1	13	11	-1	-1	-1	-1	15	-1	-1	1	-1	13	-1

- Parity-check matrix for LDPC(1008,840)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	-1	26	-1	15	0	-1	-1	-1	-1	1	-1	17	-1	21	6	-1	-1	-1	12	0	-1	-1	2	-1	-1	5	-1	13	-1	18	-1	9	12	-1	-1	15
2	-10	-1	-1	-1	7	26	-1	16	14	-1	7	-1	-1	5	20	-1	27	-1	-1	27	-1	20	-1	4	1	-1	-1	24	-1	5	-1	4	-1	24	24	-1
3	-1	10	-1	24	-1	-1	3	9	17	-1	16	-1	27	-1	24	-1	-1	21	-1	-1	21	27	12	-1	-1	10	-1	14	4	-1	6	-1	6	-1	19	-1
4	-1	7	16	-1	1	-1	26	-1	5	-1	20	-1	-1	10	-1	19	-1	7	-1	23	-1	26	-1	27	-1	21	1	-1	9	-1	9	-1	-1	3	-1	20
5	3	-1	16	-1	-1	10	24	-1	-1	11	-1	10	6	-1	-1	25	0	20	-1	-1	17	-1	4	-1	27	-1	4	-1	-1	21	17	-1	11	-1	0	-1
6	19	-1	26	-1	-1	11	-1	2	-1	14	-1	25	12	-1	-1	2	9	-1	2	-1	12	-1	-1	1	17	-1	23	-1	21	-1	-1	9	-1	20	-1	20

Appendix VI. Notes about the Link budget

1. The center frequency is taken as the middle frequency of the MICS band [402, 405] MHz
2. The RF transmission bandwidth equals Nyquist rate.
3. The transmission power is 25 uW, which is equivalent to $10\times\log10(25\times10^{-3})$= - 16dBm.
4. The transmit and receive antenna are assumed as isotropic.
5. See 4
6. The transmitter is assumed implanted 2-cm below body surface, the corresponding path loss under CM2 channel model is as $PL = PL_0 + 10\times n\times\log10(d/d_0)+S$, where PL_0=49.81dB, n=4.22, d_0=50 mm, S~N(0,6.81)
7. Additional pathloss for a distance 3 meters away from body surface is assumed as free space path loss where PL_0=24.56dB, n=2, d_0=1 m.
8. Log-normal fading margin accounts for the lognormal shadowing as suggested in the CM2 channel model.
9. Received power at 3 meters distance equals to ③+④+⑤-⑥-⑦-⑧.
10. Thermal noise power density equals to $10\log10(k_B T_e)$, where k_B=1.38e-23, T_e=273+35 K
11. Receiver noise figure comes from a worst-case assumption.
12. Receiver noise power density = receiver noise figure + thermal noise power density. ⑿ = ⑽ + ⑾
13. Received noise power = receiver noise power density + transmission bandwidth in dBHz, namely, ⒀ = ⑿ + 10log10(②×106).
14. Accounting for the interference, the link margin comes from worst-case assumption.
15. Required Eb/N0 comes from corresponding simulation in AWGN channel.
16. See 15
17. See 15
18. Receiver sensitivity = receiver noise power + link margin + required Eb/N0.
19. See 18
20. See 19

P.S. For the Nyquist rate of 3 Mbits/s, received power at 3-meter distance is lower than the required receiver sensitivity, implying that this rate cannot be supported at this distance.