IEEE P802.15
Wireless Personal Area Networks

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Abstract	[This document combines the work done thus far by TG4k into a single document.]
Purpose	[This document is the first step in preparing a draft for letter ballot.]
Notice	
Release	

IEEE Draft Standard for
Local and metropolitan area networks—

Part 15.4: Low-Rate Wireless Personal Area Networks (WPANs)

Amendment X: Physical Layer Specifications for Low Energy, Critical Infrastructure Monitoring Networks

Sponsor

LAN/MAN Standards Committee
of the
IEEE Computer Society

Abstract:
Keywords: low data rate, low power, LR-WPAN, PAN, personal area network, radio frequency, RF, wireless personal area network, WPAN

Introduction

This introduction is not part of IEEE P802.15.4k/D0.1, IEEE Draft Standard for Local and metropolitan area networks—Part 15.4: Low-Rate Wireless Personal Area Networks (WPANs)—Amendment X: Physical Layer Specifications for Low Energy, Critical Infrastructure Monitoring Networks.

This amendment specifies ...TBD

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Participants

At the time the draft of this standard was sent to sponsor ballot, the IEEE P802.15 Working Group had the following voting members:

Robert F. Heile, *Chair*
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Major contributions were received from the following individuals:

The following members of the balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention. *<insert names here>*

When the IEEE-SA Standards Board approved this standard on *DD MM* 201x, it had the following membership: *<insert names here>*

,

Also included are the following nonvoting IEEE-SA Standards Board liaisons: *<insert names here>*

IEEE Standard for
Local and metropolitan area networks—

Part 15.4: Low-Rate Wireless Personal Area Networks (WPANs)

Amendment X: Physical Layer Specifications for Low Energy, Critical Infrastructure Monitoring Networks

NOTE—The editing instructions contained in this amendment define how to merge the material contained therein into the existing base standard and its amendments to form the comprehensive standard.

The editing instructions are shown in ***bold italic***. Four editing instructions are used: change, delete, insert, and replace. ***Change*** is used to make corrections in existing text or tables. The editing instruction specifies the location of the change and describes what is being changed by using ~~strikethrough~~ (to remove old material) and <u>underscore</u> (to add new material). ***Delete*** removes existing material. ***Insert*** adds new material without disturbing the existing material. Deletions and insertions may require renumbering. If so, renumbering instructions are given in the editing instruction. ***Replace*** is used to make changes in figures or equations by removing the existing figure or equation and replacing it with a new one. Editing instructions, change markings, and this NOTE will not be carried over into future editions because the changes will be incorporated into the base standard.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

Insert the following definitions alphabetically into 3.1:

3.2 Acronyms and abbreviations

Insert the following acronyms alphabetically into 3.2:

CDMA	code division multiple access
CIC	central inventory control
CLON	co-located orthogonal network
LECIM	low energy, critical infrastructure monitoring
OVSF	orthogonal variable spreading factor
PBRI	pruned bit reversal interleaving
P-FSK	position-based frequency shift keying
P-GFSK	position-based Gaussian frequency shift keying

8. General PHY requirements

8.1 General requirements and definitions

Insert the following items at the end of the second list in 8.1:

LECIM DSSS PHY: TBD

LECIM FSK PHY: a multi-regional, frequency shift keying (FSK) PHY operating at over-the-air data rates in support of low energy, critical infrastructure monitoring (LECIM) applications.

8.1.1 Operating frequency range

Insert the following new rows at the end of table 66:

Table 66—Frequency bands and data rates

PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
470	470–510	—	GFSK/FSK	37.5	37.5	Binary
		—	GFSK/FSK	25	25	Binary
		—	FSK	12.5*	12.5*	Binary
780	779–787	—	GFSK/FSK	37.5	37.5	Binary
		—	GFSK/FSK	25	25	Binary
		—	FSK	12.5*	12.5*	Binary
863	863–870	—	GFSK/FSK	25	25	Binary
		—	FSK	12.5*	12.5*	Binary
915	902–928	—	GFSK/FSK	37.5	37.5	Binary
		—	GFSK/FSK	25	25	Binary
		—	FSK	12.5*	12.5*	Binary
917	917–923.5	—	GFSK/FSK	37.5	37.5	Binary
		—	GFSK/FSK	25	25	Binary
		—	FSK	12.5*	12.5*	Binary
920	920–928	—	GFSK/FSK	37.5	37.5	Binary
		—	GFSK/FSK	25	25	Binary
		—	FSK	12.5*	12.5*	Binary
2450	2400–2483.5	—	GFSK/FSK	37.5	37.5	Binary
		—	GFSK/FSK	25	25	Binary
		—	FSK	12.5*	12.5*	Binary

*Coordinator to end device only.

8.1.2 Channel assignments

<REVISIT> LECIM channel assignments match those used for the SUN PHY MR-FSK mode channel assignments. (Can this reference section 16? or do we want a separate channel page for LECIM?)

Table 1—Total number of channels and first channel center frequencies for LECIM FSK PHYs

Frequency band (MHz)	Modulation (uplink/ downlink)	*ChanSpacing* (MHz)	*TotalNumChan*	*ChanCenterFreq*$_0$ (MHz)
470–510	GFSK/FSK	0.2	199	470.2
779–787			39	779.2
863–870		0.1	69	863.075
902–928		0.2	129	902.2
917–923.5			32	917.1
920.5–923.5			15	920.6
2400–2483.5			416	2400.2

9. PHY services

9.2 PHY constants

9.3 PHY PIB attributes

Insert the following new rows at the end of Table 71:

Table 71—PHY PIB attributes

Attribute	Type	Range	Description
phyLECIMFSKPreambleLength	Integer	0–100	The number of 1-octet patterns, as defined in 19.2.1.1, in the preamble. This attribute is only valid for the LECIM FSK PHY.
phyLECIMFSKPSDUMod	Boolean	TRUE or FALSE	Indication of the type of modulation used. A value of TRUE indicates that P-GFSK/P-FSK is enabled for the PSDU. A value of FALSE indicates that GFSK/FSK modulation is enabled for the PSDU.
phyLECIMFSKSpreading	Boolean	TRUE or FALSE	A value of TRUE indicates that spreading is enabled. A value of FALSE indicates that spreading is disabled.
phyLECIMFSKSpreadingFactor	Integer	1, 2, 4, 8, 16	The spreading factor (SF) to be used when *phyLECIMFSKSpreading* is TRUE.
phyLECIMFSKScramblePSDU	Boolean	TRUE or FALSE	A value of FALSE indicates that data whitening of the PSDU is disabled. A value of TRUE indicates that data whitening of the PSDU is enabled. This attribute is only valid for the LECIM FSK PHY.
phyLECIMFECEnabled	Boolean	TRUE or FALSE	A value of TRUE indicates that FEC is turned on. A value of FALSE indicates that FEC is turned off. This attribute is only valid for the LECIM FSK PHY.
phyLECIMFSKInterleavingEnabled	Boolean	TRUE or FALSE	A value of TRUE indicates that interleaving is turned on. A value of FALSE indicates that interleaving is turned off. This attribute is only valid for the LECIM FSK PHY.

Insert after Clause 18 the following new clause (Clause 19):

19. LECSIM PHYs

Two PHYs are specified in order to support LECIM applications: direct sequence spread spectrum (DSSS; see 19.1) and frequency shift keying (FSK; see 19.2).

19.1 DSSS PHY specification

The direct sequence spread spectrum (DSSS) PHY is described in the following subclauses.

19.1.1 PPDU format for DSSS

For convenience, the PPDU structure is presented so that the leftmost field as written in this standard shall be transmitted or received first. All multiple octet fields shall be transmitted or received least significant octet first, and each octet shall be transmitted or received least significant bit (LSB) first.

The PPDU shall be formatted as illustrated in Figure 0.

Octets			
0/2/4	**0/1**	**0/1/2**	**Fixed/1–128/129–2048**
Preamble	SFD	See Figure 1	PSDU
SHR		PHR	PHY payload

Figure 0—Format of the LECIM DSSS PPDU

The relationship among the PPDU fields is given in Table 72.

Table 72—Relationship among the LECIM DSSS PPDU fields

Configuration	Preamble length (octets)	SFD length (octets)	PHR length (octets)	PSDU length (octets)
1	0	0	0	Fixed length
2	2/4	1	1	1–128
3	2/4	1	2	129–2048

Figure 1 shows the configuration of the PHR as a function of PHR length.

19.1.1.1 SHR

The synchronization header (SHR), if present, is used for obtaining frequency, symbol, and frame synchronization. It consists of the preamble and the start-of-frame delimiter (SFD). It is possible to recover a fixed length frame without the use of an SFD or SHR.

PHR length (octets)	PHR contents		
0	—		
1	0	Frame length (7 bits)	
2	1	Reserved (4 bits)	Frame length (11 bits)

Figure 1—PHR configuration for LECIM DSSS PHY

19.1.1.1.1 Preamble field

The Preamble field, if present, is used to obtain symbol timing and frequency offset. A preamble length of 0, 2, or 4 octets may be commissioned.

Preamble16 = [1 1 0 0 0 0 0 1 0 1 0 0 1 1 0]

Preamble32 = [T.B.D.]

19.1.1.1.2 SFD field

The SFD field, if present, indicates the beginning of the frame.

SFD = [T.B.D.]

19.1.1.2 PHR

The PHY header (PHR) is used to indicate the length of a variable length PHY payload. When the PHY payload is commissioned to a fixed size, the PHR is elided. For variable length PHY payloads of up to 128 octets, the PHR is one octet and represents a payload of $n + 1$ octets where $n = 0 \ldots 127$. For variable length PHY payloads of 129–2048 octets, the PHR is two octets. The bit definitions of the one and two octet PHRs are illustrated in Figure 1.

19.1.2 Modulation and spreading

19.1.2.1 Data rate

The data rate is band and/or region specific. Table 73 gives the frequency bands and data rates for the DSSS PHY.

The channelization for the 868 MHz band is as follows:

— Channel 0: 868.300 MHz
— Channel 1: 868.950 MHz
— Channel 2: 869.525 MHz

The channel numbering and spacing for the 902 MHz band are as follows:

$$904 + [(n - 1) \times 1.99\ \text{MHz}]$$

where $n = 1 \ldots 15$.

Table 73—Frequency bands and data rates for LECIM DSSS PHY

PHY (MHz)	Frequency band (MHz)	Region/availability	Chip rate (kchip/s)	Modulation
400	400–470	South Korea	100 (12.5 kHz channel bonded)	BPSK/?
470	470–510	China		BPSK/O-QPSK
				BPSK/O-QPSK
				BPSK/O-QPSK
780	779–787	China		BPSK/O-QPSK
				BPSK/O-QPSK
				BPSK/O-QPSK
868	863–870	EU/CEPT	100	BPSK/O-QPSK
902	902–928	Americas, Austrailia	1000/?	BPSK/O-QPSK
917	917–923.5	South Korea		BPSK/O-QPSK
				BPSK/O-QPSK
				BPSK/O-QPSK
920	920–928	Japan	200	BPSK/O-QPSK
			600	BPSK/O-QPSK
			1000	BPSK/O-QPSK
2450	2400–2483.5	Worldwide	1000, 2000?	BPSK/O-QPSK

The channel numbering and spacing for the 2400 MHz band are as follows:

$$2402 + [(n - 1) \times 1.99 \text{ MHz}]$$

where $n = 1 \ldots 41$.

The 1.99 MHz spacing is used to minimize false lock and interference from spurious.

19.1.2.2 Reference modulator diagram

The functional block diagram in Figure 2 is provided as a reference for specifying the LECIM DSSS PHY modulation. All binary data contained in the SHR, PHR, and PSDU shall be encoded using the modulation shown in Figure 2.

19.1.2.3 Convolutional forward error correction (FEC) encoding

The convolutional encoder is the same as specified in the IEEE Std 802.11™-2007.

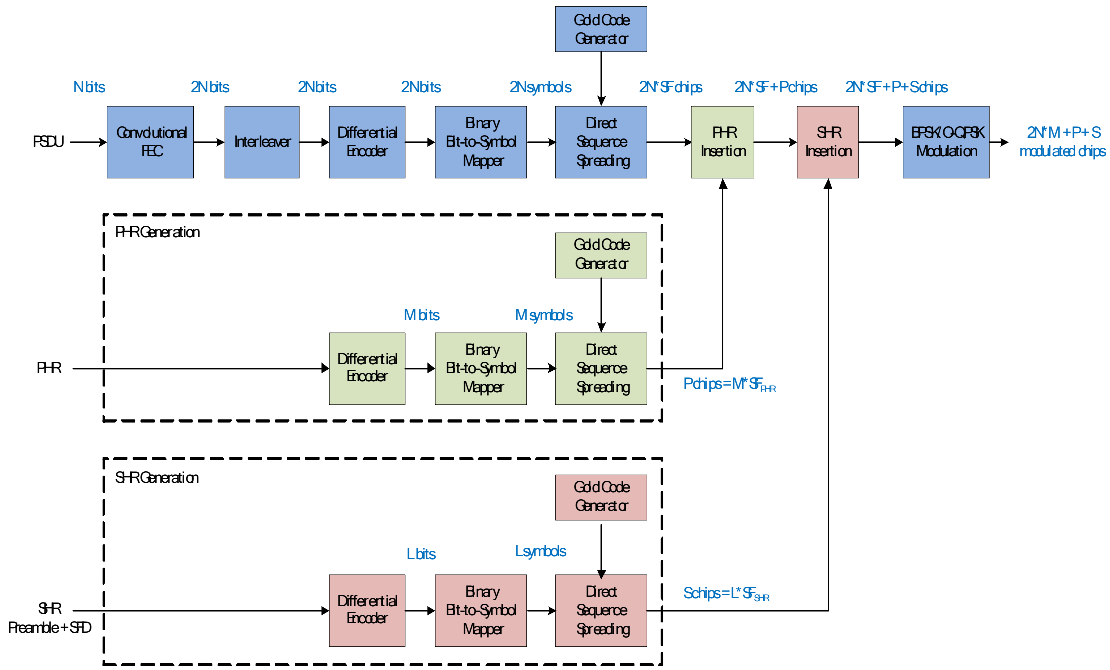

Figure 2—LECIM DSSS reference modulator diagram

The PSDU and tail/pad parts shall be coded with a convolutional encoder of coding rate R = 1/2. The convolutional encoder shall use the industry standard generator polynomials $g_0 = 133_8$ and $g_1 = 171_8$ of rate R = 1/2, as shown in Figure 3.

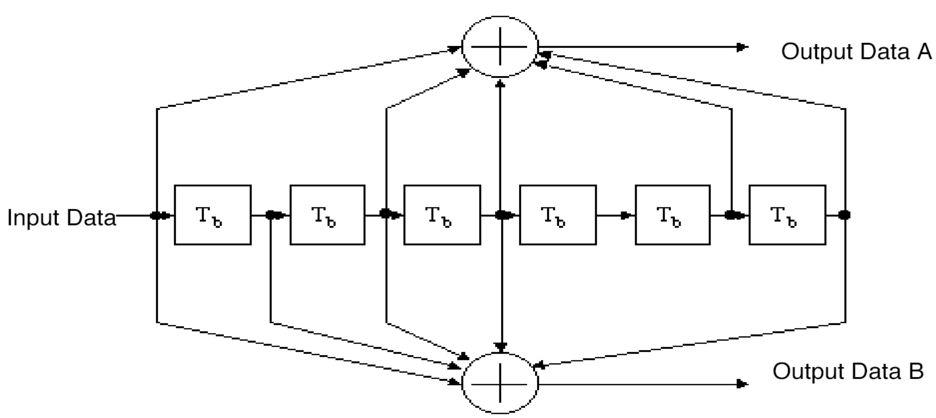

Figure 3—Convolutional encoder (k=7) for LECIM DSSS PHY

19.1.2.4 Interleaver

The output of the convolutional coder is interleaved using a pruned bit reversal interleaving (PBRI) algorithm.

The text that follows contains examples of bit reverse interleavers for three fragment sizes (256, 384, 512 symbols). Fragment sizes that are not powers of two (e.g., 384) employ pruning.

19.1.2.4.1 256 symbol fragment size

If the input sequence into the interleaver is represented by

$$[S_0\ S_1 \ldots S_{255}]$$

Then the output sequence of the interleaver can be described as

$$[S_0\ S_{16} \ldots S_N\ S_{255}]$$

The value *N* for the M^{th} output is determined as the bit-reversal of the value *M*.

Representing the value *M* as a binary representation

$$M = [m_7\ m_6 \ldots m_0]$$

where m_i are the binary digits, then

$$N = [m_0\ m_1 \ldots m_7]$$

where *M* is incremented sequentially from 0 to 255.

The sequence of *N* is thus,

0 128 64 192 32 160 96 224 16 144 80 208 48 176 112 240 8 136 72 200
40 168 104 232 24 152 88 216 56 184 120

248 4 132 68 196 36 164 100 228 20 148 84 212 52 180 116 244 12 140 76
204 44 172 108 236 28 156 92 220 60 188 124 252 2 130 66 194 34 162 98 226
18 146 82 210 50 178 114 242 10 138 74 202 42 170 106 234 26 154 90 218 58
186 122 250 6 134 70 198 38 166 102 230 22 150 86 214 54 182 118 246 14
142 78 206 46 174 110 238 30 158 94 222 62 190 126 254 1 129 65 193 33 161
97 225 17 145 81 209 49 177 113 241 9 137 73 201 41 169 105 233 25 153 89
217 57 185 121 249 5 133 69 197 37 165 101 229 21 149 85 213 53 181 117
245 13 141 77 205 45 173 109 237 29 157 93 221 61 189 125 253 3 131 67 195
35 163 99 227 19 147 83 211 51 179 115 243 11 139 75 203 43 171 107 235 27
155 91 219 59 187 123 251 7 135 71 199 39 167 103 231 23 151 87 215 55 183
119 247 15 143 79 207 47 175 111 239 31 159 95 223 63 191 127 255

19.1.2.4.2 384 symbol fragment size

If the input sequence into the interleaver is represented by

$$[S_0\ S_{1\ldots}S_{383}] \qquad (1)$$

Then the output sequence of the interleaver can be described as

$$[S_0\ S_{16} \ldots S_N\ S_{383}]$$

Representing the value *M* as a binary representation

$$M' = [m'_8\ m'_6 \ldots m'_0]$$

where m_i are the binary digits, then

$$N = [m'_0\ m'_1 \ldots m'_8]$$

where *M* is incremented sequentially from 0 to 512 and *M*' are the ordered set of *M* whose corresponding *N* is less than 384 (this is the pruning process).

The sequence of *N* is thus,

0 256 128 64 320 192 32 288 160 96 352 224 16 272 144 80 336 208 48 304
176 112 368 240 8 264 136 72 328 200 40 296 168 104 360 232 24 280 152 88
344 216 56 312 184 120 376 248 4 260 132 68 324 196 36 292 164 100 356 228
20 276 148 84 340 212 52 308 180 116 372 244 12 268 140 76 332 204 44 300
172 108 364 236 28 284 156 92 348 220 60 316 188 124 380 252 2 258 130 66
322 194 34 290 162 98 354 226 18 274 146 82 338 210 50 306 178 114 370 242
10 266 138 74

330 202 42 298 170 106 362 234 26 282 154 90 346 218 58 314 186 122 378 250
6 262 134 70 326 198 38 294 166 102 358 230 22 278 150 86 342 214 54 310 182
118 374 246 14 270 142 78 334 206 46 302 174 110 366 238 30 286 158 94 350
222 62 318 190 126 382 254 1 257 129 65 321 193 33 289 161 97 353 225 17
273 145 81 337 209 49 305 177 113 369 241 9 265 137 73 329 201 41 297 169
105 361 233 25 281 153 89 345 217 57 313 185 121 377 249 5 261 133 69 325
197 37 293 165 101 357 229 21 277 149 85 341 213 53 309 181 117 373 245 13
269 141 77 333 205 45 301 173 109 365 237 29 285 157 93 349 221 61 317 189
125 381 253 3 259 131 67 323 195 35 291 163 99 355 227 19 275 147 83 339
211 51 307 179 115 371 243 11 267 139 75 331 203 43 299 171 107 363 235 27
283 155 91 347 219 59 315 187 123 379 251 7 263 135 71 327 199 39 295 167
103 359 231 23 279 151 87 343 215 55 311 183 119 375 247 15 271 143 79 335
207 47 303 175 111 367 239 31 287 159 95 351 223 63 319 191 127 383 255

19.1.2.4.3 512 symbol fragment size

If the input sequence into the interleaver is represented by

$$[S_0\ S_1 \ldots S_{255}]$$

Then the output sequence of the interleaver can be described as

$$[S_0\ S_{16} \ldots S_N\ S_{255}]$$

The value *N* for the M^{th} output is determined as the bit-reversal of the value *M*.

Representing the value *M* as a binary representation

$$M = [m_8\ m_6 \ldots m_0]$$

where m_i are the binary digits, then

$$N = [m_0\ m_1 \ldots m_8]$$

where M is incremented sequentially from 0 to 511.

The sequence of N is thus,

0 256 128 384 64 320 192 448 32 288 160 416 96 352 224 480 16 272 144 400
80 336 208 464 48 304 176 432 112 368 240 496 8 264 136 392 72 328 200 456
40 296 168 424 104 360 232 488 24 280 152 408 88 344 216 472 56 312 184 440
120 376 248 504 4 260 132 388 68 324 196 452 36 292 164 420 100 356 228 484
20 276 148 404 84 340 212 468 52 308 180 436 116 372 244 500 12 268 140 396
76 332 204 460 44 300 172 428 108 364 236 492 28 284 156 412 92 348 220 476
60 316 188 444 124 380 252 508 2 258 130 386 66 322 194 450 34 290 162 418
98 354 226 482 18 274 146 402 82 338 210 466 50 306 178 434 114 370 242 498
10 266 138 394 74 330 202 458 42 298 170 426 106 362 234 490 26 282 154 410
90 346 218 474 58 314 186 442 122 378 250 506 6 262 134 390 70 326 198 454
38 294 166 422 102 358 230 486 22 278 150 406 86 342 214 470 54 310 182 438
118 374 246 502 14 270 142 398 78 334 206 462 46 302 174 430 110 366 238 494
30 286 158 414 94 350 222 478 62 318 190 446 126 382 254 510 1 257 129 385
65 321 193 449 33 289 161 417 97 353 225 481 17 273 145 401 81 337 209 465
49 305 177 433 113 369 241 497 9 265 137 393 73 329 201 457 41 297 169 425
105 361 233 489 25 281 153 409 89 345 217 473 57 313 185 441 121 377 249 505
5 261 133 389 69 325 197 453 37 293 165 421 101 357 229 485 21 277 149 405
85 341 213 469 53 309 181 437 117 373 245 501 13 269 141 397 77 333 205 461
45 301 173 429 109 365 237 493 29 285 157 413 93 349 221 477 61 317 189 445
125 381 253 509 3 259 131 387 67 323 195 451 35 291 163 419 99 355 227 483
19 275 147 403 83 339 211 467 51 307 179 435 115 371 243 499 11 267 139 395
75 331 203 459 43 299 171 427 107 363 235 491 27 283 155 411 91 347 219 475
59 315 187 443 123 379 251 507 7 263 135 391 71 327 199 455 39 295 167 423
103 359 231 487 23 279 151 407 87 343 215 471 55 311 183 439 119 375 247 503
15 271 143 399 79 335 207 463 47 303 175 431 111 367 239 495 31 287 159 415
95 351 223 479 63 319 191 447 127 383 255 511

19.1.2.5 Differential encoding

The differential encoding of the DSSS PHY is described in 11.2.3.

19.1.2.6 Bit-to-symbol and symbol-to-chip encoding

The bit-to-symbol mapper converts bits into binary symbols through the mapping:

$$x[n] = \begin{cases} 1, & \text{if } b[n] = 0 \\ -1, & \text{if } b[n] = 1 \end{cases}$$

These binary symbols are then spread to chip-rate with spreading factor SF. This process is illustrated explicitly in Figure 4 where SF = 8. The symbols are first up-sampled SF times and interpolated using a scaled boxcar filter, as shown in Figure 5, i.e., the symbol is repeated SF times at chip-rate. Note that this is a mathematical representation of the direct sequence spreading operation. This process can be implemented in an alternative manner that is mathematically equivalent. The up-sampled symbols are multiplied by a specified Gold code to create the spread signal.

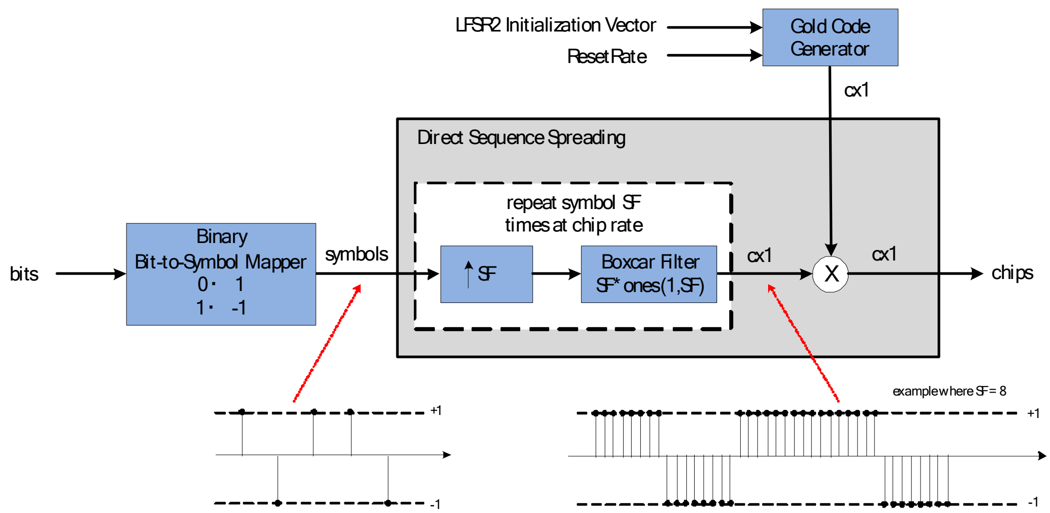

Figure 4—Bit-to-chip diagram for LECIM DSSS PHY

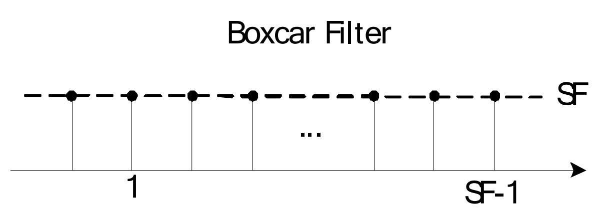

Figure 5—Boxcar filter

19.1.2.6.1 Gold code generator

Gold code sequences are a large family of easily parameterized PN sequences with good periodic cross-correlation and off-peak auto-correlation properties. A Gold code sequence is derived from the binary addition (XOR) of two maximum length sequences (*m*-sequences, or MLS), as illustrated in Figure 6. The *m*-sequences are generated using Fibonacci linear feedback shift registers (LFSR). Each LFSR is constructed from primitive (or prime) polynomials over Galois field 2 (GF[2]). The resulting sequences thus constitute segments of a set of Gold sequences. The specific *m*-sequences that follow are the preferred pair as described in the 3rd Generation Partnership Project (3GPP) Technical Specification 25.213. The Gold sequence can be parameterized by setting the initialization vector of LFSR2 to different values (LFSR1 is always initialized to 0x1).

— $m = 25$ (length of LSFR)
— $n = 2m - 1 = 33{,}554{,}431$ (length of Gold code)
— $n + 2 = 33{,}554{,}433$ (total Gold sequences) = a, b, $a \times b$, $a \times Tb$, $a \times T2b$, …

LFSR (MLS) generator polynomials:

— $p1(x) = x^{25} + x^3 + 1$
— $p2(x) = x^{25} + x^3 + x^2 + x + 1$

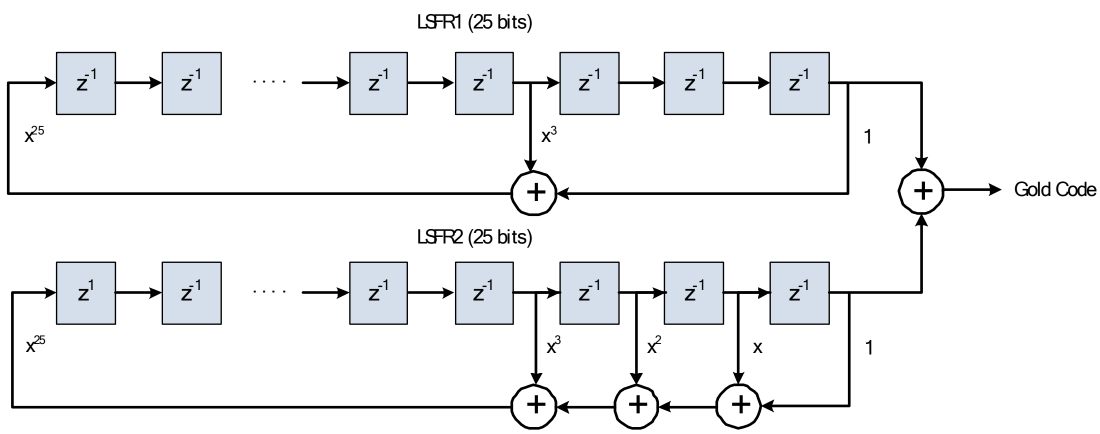

Figure 6—Gold code generator

19.1.2.6.2 OVSF code generator

The orthogonal variable spreading factor (OVSF) code is the same as the Walsh code, except that each sequence has a different index number in the code set, which is a result of their different generation algorithms.

The Gold code is to be used inside a co-located orthogonal network (CLON) as a primary code. OVSF codes are to be used to preserve orthogonality to identify the CLONs and clusters. It will provide double protection from outside interference.

The OVSF code is a linear code over a binary alphabet that maps messages of length n to codewords of length $2n$, and is generated from a Hadamard matrix but with the permutation matrix concept.

To reconstruct the OVSF code, recursively define a sequence of codes C_i as follows. Let C_0 be the root [1]. Assuming that C_i has been defined, for $i < r$, define C_{i+1} by

$$C_{i+1} = \begin{cases} C_i C_i, & \text{if } x_i = 0 \\ C_i(-C_i), & \text{if } x_i = 1 \end{cases}$$

The code C_N has the specified spreading factor and code index.

OVSF codes can also be defined recursively by a tree structure, as shown in Figure 7.

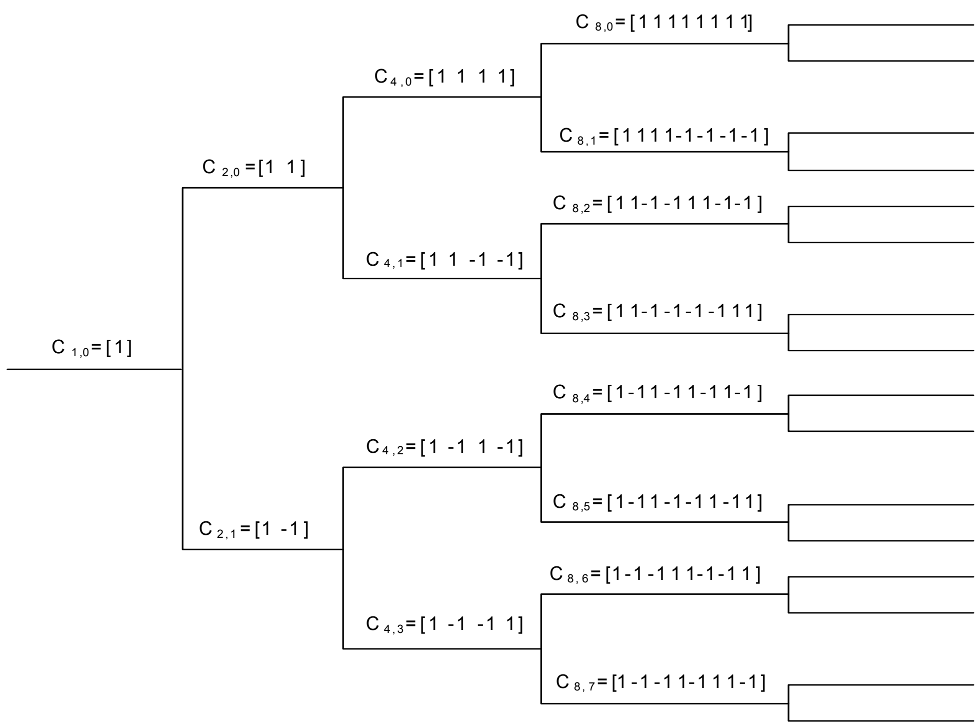

Figure 7—OVSF codes recursively defined by tree structure

19.1.2.7 BPSK/O-QPSK modulation

19.1.2.7.1 BPSK modulation

Binary phase-shift keying (BPSK) modulation for the DSSS PHY is described in 11.2.5.

The chip sequences are modulated onto the carrier using BPSK with raised cosine pulse shaping (roll-off factor = 1), where a chip value of one corresponds to a positive pulse and a chip value of zero corresponds to a negative pulse.

Chip rates/bands shown in Table TBD.

The pulse shape is described in 11.2.5.1.

During each symbol period, the least significant chip is transmitted first, and the most significant chip is transmitted last.

(further clarification on what is meant by least and most significant bit)

19.1.2.7.2 O-QPSK modulation

The chip sequences representing each data symbol are modulated onto the carrier using offset quadrature phase-shift keying (O-QPSK) with pulse shaping. For an even-indexed symbol, the even-indexed chips are modulated onto the in-phase (I) carrier, and odd-indexed chips are modulated onto the quadrature-phase (Q) carrier. For an odd-indexed symbol, even-indexed chips are modulated onto the quadrature-phase (Q) carrier, and odd-indexed chips are modulated onto the in-phase (I) carrier. To form the offset between I-phase and Q-phase chip modulation, the Q-phase chips shall be delayed by T_c with respect to the I-phase chips, as illustrated in Figure 8, where T_c is the inverse of the chip rate.

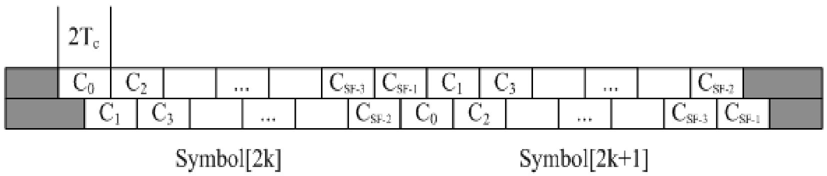

Figure 8—O-QPSK chip modulation

The pulse shape - 4g 16.3.2.13 Modulation parameters doe O-QPSK? Why multiple shapes?

The chip transmission order is the same as 10.2.7 - ?

During each symbol period, the least significant chip, C_0, is transmitted first, and the most significant chip, C_{SF-1}, is transmitted last.

(further clarification on what is meant by least and most significant bit or reference Figure 8 C_{SF-1})

19.2 FSK PHY specification

The frequency shift keying (FSK) PHY is described in the following subclauses.

19.2.1 PPDU format for FSK

The FSK PPDU shall support the format shown in Figure 9.

The synchronization header (SHR), PHY header (PHR), and PHY payload components are treated as bit strings of length *n*, numbered b_0 on the left and b_{n-1} on the right. When transmitted, they are processed b_0 first to b_{n-1} last, without regard to their content or structure.

All reserved fields shall be set to zero upon transmission and shall be ignored upon reception.

19.2.1.1 Preamble field

The Preamble field shall contain *phyLECIMFSKPreambleLength* (as defined in 9.3) multiples of the 8-bit sequence "01010101."

Given the asymmetric nature of LECIM networks, greater capabilities of coordinators and low energy end devices, the range of preamble length is 0 to 100 octets. High functioning coordinators may need little or no

		Octets	
		N	**variable**
Preamble	SFD	As defined in 19.2.1.3	PSDU
SHR		PHR	PHY payload

Figure 9—Format of the LECIM FSK PPDU

preamble to synchronize, which reduces the transmit times of battery devices. A maximum preamble length of 100 is sufficient for the radios in end devices to synchronize for transmission.

19.2.1.2 SFD

The SFD shall be a 3-octet sequence, as shown in Table 74.

The SFD is transmitted starting from the leftmost bit (i.e., starting with b_0).

Table 74—SFD value for LECIM FSK PHY

Octets	1	2	3
Bit map	xxxxxxx	xxxxxxx	xxxxxxx

19.2.1.3 PHR

The formats of the PHR are shown for 127 and 2047 octet packets in Figure 10 and Figure 11, respectively. All multi-bit fields are unsigned integers and shall be processed MSB first.

The Frame Length field can be either 7 or 12 bits, for 127 and 2047 octet packets, respectively. The value of the Extension Bit field indicates which field length is used. The Frame Length field specifies the total number of octets contained in the PSDU (prior to FEC encoding, if enabled). The most significant bit (leftmost) shall be transmitted first.

It is important to note that LECIM networks are commissioned networks and strive to minimize energy consumption in battery-powered end devices. As such, not all parameters are signaled with bits in the PHR, but are instead assumed to be programmed into the network devices at commissioning. The parameters configuring the use of data whitening, FEC, interleaving, spreading, modulation type, and FCS length are considered commissioned parameters and are not signaled in the PHR.

Bit string index	0	1–7
Bit mapping	0	L_6–L_0
Field name	Extension Bit	Frame Length

Figure 10—PHR for 127 octet packet

Bit string index	0	1–3	1–12
Bit mapping	1	R_2–R_0	L_{11}–L_0
Field name	Extension Bit	Reserved	Frame Length

Figure 11—PHR for 2047 octet packet

19.2.1.4 PSDU field

The PSDU field carries the data of the PPDU.

19.2.2 Modulation and coding for FSK

The modulation for the FSK PHY shall be FSK/Gaussian FSK (GFSK) and position-based FSK (P-FSK)/ position-based GFSK (P-GFSK).

Table 75 shows the modulation and channel parameters for the standard-defined PHY operating modes for the 863 MHz, 915 MHz, 917 MHz, 920 MHz, and 2450 MHz bands.

Although there are multiple data rates for each frequency band in Table 75, there is no over-the-air, dynamic data rate changing mechanism defined for this PHY. It is left to the system designer to select the appropriate data rates for the deployment during the design and commissioning of each specific network. The LECIM FSK PHY is not intended to be a multi-rate PHY with over-the-air signaling of changing data rates.

Table 75—LECIM FSK modulation and channel parameters*

Frequency band (MHz)	Parameter	37.5 kbps	25 kbps	12.5 kbps
470–510 (China)	End device to coordinator	GFSK/P-GFSK	GFSK/P-GFSK	Not supported
	Coordinator to end device	FSK/P-FSK	FSK/P-FSK	FSK
	Modulation index	0.5	1.0	4.0
	Channel spacing (kHz)	200	200	200
779–787 (China)	End device to coordinator	GFSK/P-GFSK	GFSK/P-GFSK	Not supported
	Coordinator to end device	FSK/P-FSK	FSK/P-FSK	FSK
	Modulation index	0.5	1.0	4.0
	Channel spacing (kHz)	200	200	200
863–870 (Europe)	End device to coordinator	Not supportable due to regulations	GFSK/P-GFSK	Not supported
	Coordinator to end device	Not supportable due to regulations	FSK/P-FSK	FSK
	Modulation index	0.5	1.0	4.0
	Channel spacing (kHz)	100	100	100

Table 75—LECIM FSK modulation and channel parameters* *(continued)*

Frequency band (MHz)	Parameter	37.5 kbps	25 kbps	12.5 kbps
902–928 (US ISM)	End device to coordinator	GFSK/P-GFSK	GFSK/P-GFSK	Not supported
	Coordinator to end device	FSK/P-FSK	FSK/P-FSK	FSK
	Modulation index	0.5	1.0	4.0
	Channel spacing (kHz)	200	200	200
917–923.5 (Korea)	End device to coordinator	GFSK/P-GFSK	GFSK/P-GFSK	Not supported
	Coordinator to end device	FSK/P-FSK	FSK/P-FSK	FSK
	Modulation index	0.5	1.0	4.0
	Channel spacing (kHz)	200	200	200
920–928 (Japan)	End device to coordinator	GFSK/P-GFSK	GFSK/P-GFSK	Not supported
	Coordinator to end device	FSK/P-FSK	FSK/P-FSK	FSK
	Modulation index	0.5	1.0	4.0
	Channel spacing (kHz)	200	200	200
2400–2483.5 (Worldwide)	End device to coordinator	GFSK/P-GFSK	GFSK/P-GFSK	Not supported
	Coordinator to end device	FSK/P-FSK	FSK/P-FSK	FSK
	Modulation index	0.5	1.0	4.0
	Channel spacing (kHz)	200	200	200

*Data rates shown are over-the-air data rates (the data rate transmitted over the air regardless whether the FEC is enabled or not).

The symbol duration used for the MAC and PHY timing parameters are shown in Table 76.

Table 76—LECIM FSK symbol duration used for MAC and PHY timing parameters

Frequency band (MHz)	FSK symbol timing used for MAC and PHY timing parameters (μs)
470–510 (China)	26.67
779–787 (China)	40
863–870 (Europe)	40
902–928 (US ISM)	26.67
917–923.5 (Korea)	26.67
920–928 (Japan)	26.67
2400–2483.5 (Worldwide)	26.67

The use of P-FSK/P-GFSK modulation for PSDU data is controlled by the PIB attribute *phyLECIMFSKPSDUMod*, as defined in 9.3. The modulation for preamble, SFD, and PHR shall be FSK/GFSK regardless of the value of *phyLECIMFSKPSDUMod*.

FSK/GFSK encodes one bit by transmitting a frequency modulated signal $m(t)$ with duration T_S, i.e., $0 \le t < T_S$. P-FSK/P-GFSK encodes two bits by transmitting a FSK/GFSK modulated signal $m(t)$ with T_s duration in one of two possible positions (also known as time deviation), i.e., $0 \le t < T_S$ and $T_S \le t < 2T_S$.

19.2.2.1 Reference modulator diagram

The functional block diagram in Figure 12 is provided as a reference for specifying the FSK PHY data flow processing functions. The subclause number in each block refers to the subclause that describes that function. Each bit shall be processed using the bit order rules defined in 19.2.1.

When FEC is enabled, the PHR and PSDU shall be processed for coding as a single block of data, as described in 19.2.2.4. When data whitening is enabled, the scrambling shall be only applied over the PSDU, as described in 19.2.3. When spreading is enabled, the spreading shall be applied over the PHR and PSDU, as described in 19.2.2.6.

All fields in the PPDU shall use the same symbol rate and modulation order, unless otherwise specified elsewhere in this standard.

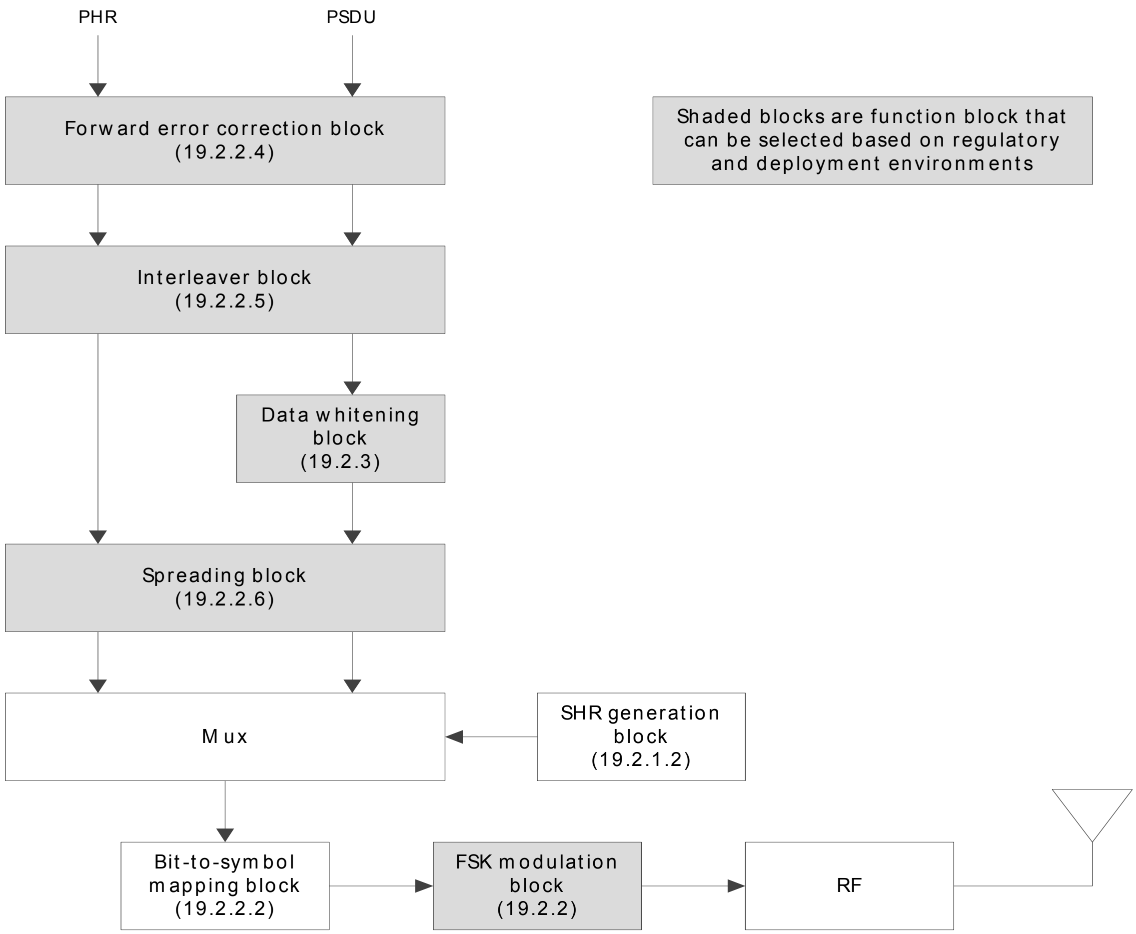

Figure 12—LECIM FSK reference modulator diagram

19.2.2.2 Bit-to-symbol mapping

The nominal frequency deviation, Δf, shall be

$$\frac{(\text{symbol rate} \times \text{modulation index})}{2}$$

The symbol encoding for FSK/GFSK and P-FSK/GFSK modulation is shown in Table 77 and Table 78, respectively, where the maximum frequency deviation, f_{dev}, is equal to Δf.

19.2.2.3 Modulation quality

Modulation quality shall be measured by observing the frequency deviation tolerance and the zero crossing tolerance of the eye diagram caused by a PN9 sequence of length 511 bits.

Table 77—FSK/GFSK symbol encoding

Symbol (b_0)	Frequency deviation	Time deviation
0	$-f_{dev}$	0
1	$+f_{dev}$	0

Table 78—P-FSK/P-GFSK symbol encoding

Symbol (b_0, b_1)	Frequency deviation	Time deviation
00	$-f_{dev}$	0
01	$-f_{dev}$	T_s
10	$+f_{dev}$	0
11	$+f_{dev}$	T_s

19.2.2.3.1 Frequency deviation tolerance

The GFSK modulation frequency tolerance is measured as a percentage of the frequency deviation dictated by the modulation index. The measured frequency deviation shall be ± 30% of the ideal frequency deviation, as shown in Figure 109 of 16.1.2.3.1. A binary one shall be represented by a positive frequency deviation, and a binary zero shall be represented by a negative frequency deviation.

The symbol timing shall be less than ± 20 ppm.

19.2.2.3.2 Zero crossing tolerance

The excursions for the zero crossings for all trajectories of the eye diagram shall be constrained as specified in 16.1.2.3.2.

19.2.2.4 Forward error correction

The FSK PHY shall perform FEC as defined in 16.3.2.6. The use of FEC is controlled by the PIB attribute *phyLECIMFECEnabled*, as defined in 9.3.

19.2.2.5 Code-symbol interleaving

The FSK PHY shall perform interleaving as defined in 16.1.2.5. The use of interleaving is controlled by the PIB attribute *phyLECIMFSKInterleavingEnabled*, as defined in 9.3.

19.2.2.6 Spreading

The use of spreading is controlled by the PIB attribute *phyLECIMFSKSpreading*, as defined in 9.3. The spreading factor (SF) can be 1, 2, 4, 8, or 16. The variable SF is indicated by the PIB attribute *phyLECIMFSKSpreadingFactor*, as defined in 9.3.

For spreading, a single input bit (b_0) is mapped into the spreading bits $(c_0, c_1, \ldots, c_{SF-1})$, as shown in Figure 13, and its mapping is represented in Table 79.

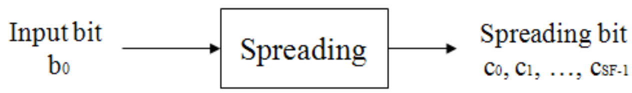

Figure 13—Spreading function

Table 79—Input bit to spreading bits mapping

Spreading factor (SF)	Input bit $(b_0) = 0$	Input bit $(b_0) = 1$
1	$(c_0) = 0$	$(c_0) = 1$
2	$(c_0, c_1) = 01$	$(c_0, c_1) = 10$
4	$(c_0, \ldots, c_3) = 0101$	$(c_0, \ldots, c_3) = 1010$
8	$(c_0, \ldots, c_7) = 0101\ 0101$	$(c_0, \ldots, c_7) = 1010\ 1010$
16	$(c_0, \ldots, c_{15}) = 0101\ 0101\ 0101\ 0101$	$(c_0, \ldots, c_{15}) = 1010\ 1010\ 1010\ 1010$

19.2.3 Data whitening for FSK

The FSK PHY may optionally perform data whitening as defined in 16.1.3. The use of data whitening is controlled by the PIB attribute *phyLECIMFSKScramblePSDU*, as defined in 9.3.

19.2.4 FSK PHY RF requirements

19.2.4.1 Operating frequency range

The FSK PHY operates in the bands given in Table 75.

19.2.4.2 Regulatory compliance

It is the responsibility of the implementer to verify and ensure that the device is in compliance with all regulatory requirements in the geographic region where the device is deployed or sold. Conformance with this standard does not guarantee compliance with the relevant regulatory requirements which may apply.

19.2.4.3 Radio frequency tolerance

The single-sided clock frequency tolerance T at the transmitter, in ppm, shall be as follows:

$$T = 20 \text{ ppm}$$

19.2.4.4 Channel switch time

Channel switch time shall be less than or equal to 500 µs. The channel switch time is defined as the time elapsed when changing to a new channel, including any required settling time.

19.2.4.5 Transmit spectral mask

Implementers are responsible to assure that the transmit spectral content conforms to all local regulations.

19.2.4.6 Receiver sensitivity

Under the conditions specified in 8.1.7, a compliant PHY device shall be capable of achieving a sensitivity of –95 dBm or better.

19.2.4.7 Receiver interference rejection

The minimum receiver interference rejection levels are given in Table 80. The adjacent channels are the ones on either side of the desired channel that are closest in frequency to the desired channel, and the alternate channels are one more removed from the adjacent channels. For example, when channel 15 is the desired channel, channel 14 and channel 16 are the adjacent channels, and channel 13 and channel 17 are the alternate channels.

Table 80—Minimum receiver interference rejection requirements

Adjacent channel rejection	Alternate channel rejection
10 dB	30 dB

The adjacent channel rejection shall be measured as follows. The desired signal shall be a compliant GFSK/FSK PHY signal, as defined by 19.2.2, of pseudo-random data. The desired signal is input to the receiver at a level 3 dB greater than the maximum allowed receiver sensitivity given in 19.2.4.6.

In either the adjacent or the alternate channel, a compliant signal, as defined by 19.2.2, is input at the level specified in Table 80 relative to the desired signal. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 8.1.7 under these conditions.

19.2.4.8 Tx-to-Rx turnaround time

The FSK PHY shall meet the requirements for TX-to-RX turnaround time as defined in 8.2.1.

19.2.4.9 Rx-to-Tx turnaround time

The FSK PHY shall meet the requirements for RX-to-TX turnaround time as defined in 8.2.2.

19.2.4.10 Transmit power

A transmitter shall be capable of transmitting at least –3 dBm. The maximum transmit power is limited by local regulatory bodies.

Insert after Annex O the following new annex (Annex P):

Annex P

(informative)

Low Energy, Critical Infrastructure Monitoring Systems

P.1 Introduction

As per Wikipedia (http://en.wikipedia.org/wiki/Critical_infrastructure): Critical infrastructure is a term used by governments to describe assets that are essential for the functioning of a society and economy. Most commonly associated with the term are facilities for:

- Electricity generation, transmission, and distribution
- Gas production, transport, and distribution
- Oil and oil products production, transport, and distribution
- Telecommunication
- Water supply (e.g., drinking water, waste water/sewage, stemming of surface water [e.g., dikes and sluices])
- Agriculture, food production, and distribution
- Heating (e.g., natural gas, fuel oil, district heating)
- Public health (e.g., hospitals, ambulances)
- Transportation systems (e.g., fuel supply, railway network, airports, harbors, inland shipping)
- Financial services (e.g., banking, clearing)
- Security services (e.g., police, military)

P.1.1 LECIM characteristics

The LECIM portions of this standard form the MAC and PHY behaviors that implement a minimal network infrastructure, enables the collection of scheduled and event data from a large number of non-mains powered end points that are widely dispersed, or are in challenging propagation environments. To facilitate low energy operation necessary for multi-year battery life, MAC protocols minimize network maintenance traffic and device wake durations. In addition, LECIM addresses the changing propagation and interference environments encountered over many years.

The following is a list of LECIM characteristics and the underlying behaviors that form them:

a) Minimal infrastructure
   - Star topology, i.e., no repeaters are typically needed due long range.
   - Mains energy supply is only necessary for coordinator.

b) Commissioned network (not ad hoc)
   - Devices are configured specifically for the deployed network.
   - Devices are stateful, i.e., they are preconfigured with parameters that eliminate the need for wireless messages sending configuration information.

c) Long range
   - High receiver sensitivity, e.g., narrow bandwidth or high processing gain.

   - Interference robustness.
   - Challenging environments and widely dispersed devices.

d) Very limited energy supplied endpoints
   - Ten to twenty year life with no maintence, e.g., original battery must supply all energy for 20 years.
   - Energy harvesting with low power supplies, i.e., short and infrequent transmission and reception durations.

e) Significant difference between coordinator and endpoints
   - Does not preclude distributed systems.

f) Asymmetrical data flows
   - Sensor end point: up-link dominates data flow with limited down-link data needs.
   - Actuator end point: down-link dominates data flow with limited up-link data needs.

P.1.2 Use case examples

The following use cases exemplify LECIM applications.

P.1.2.1 Oil and gas pipeline monitoring

The key drivers of pipeline monitoring are as follows:

- Environmental protection
- Reliability (critical resources)
- Cost savings (increasing cost)
- Compliance (regulators)

P.1.2.2 Water leak detection

The key drivers of water leak detection are as follows:

- Permanent installation of large number of sensors underground
- Long range and ability to penetrate underground vaults
- Battery operated and long lifetime
  - Small data messages once per day and in case of alarm event (e.g., leak detected)
- Low installation cost (easy deployment) and low cost of maintenance

P.1.2.3 Soil monitoring

The key drivers of soil monitoring are as follows:

- Power consumption
  - Low-cost batteries that last over many years
- Networking
  - Long range links to cover large fields
  - Ability to use mesh or tree networking for complicated environment
  - Ability to connecting WPAN with mobile networks
- Reliability and cost
  - Very low maintence requirements

P.1.2.4 Inventory control - event driven with query

The application is for a warehouse floor with thousands of parts bins. Each bin has a battery operated RF link for communicating current quantity and changes in quantity to the central inventory control (CIC) system. Battery life is important.

Each bin contains only one part number. The RF link has an LCD display showing the quantity in the bin. It also has an “Increase Button” and a “Decrease Button.” When an operator adds units to the bin, he presses the Increase Button, and when parts are removed, he presses the Decrease Button. Each time a button is pressed, it generates an event to the RF module, which then transmits the change to the CIC. This would most likely use a contention access method for transmission, since events occur in an unscheduled manner.

The CIC receives events from all of the bins, as changes are made to the quantity contained in each bin. Both the local RF module and the CIC maintain the quantity in the bin.

For inventory auditing, it is necessary for the CIC to query each bin to check the quantity. This requires the CIC to initiate a transaction with each bin, either individually or as a broadcast/multicast message. The desire is to have all bins report within a reasonable time (minutes).

Also, since changes in quantity are event driven, the CIC need a means to query each bin to make sure that it is still operational and that no "change in quantity" events were missed.

To minimize battery drain, the LECIM device is only activated when necessary:

- A change in quantity as indicated by a button event
- Some type of synchronous sniff/query operation for receiving to queries from CIC
- Response to query messages

P.1.2.5 Building monitoring - time and event driven data with query

A building (or any structure) is being monitored by sensors that report measurement or state information over long periods, e.g., several minutes to several hours. There may also be sensors that report events or changes in state that are event driven and not time driven. Battery life is important.

Each measurement sensor is set to report its information at a certain interval, using either a GTS or the CAP. This gives very low duty cycle for normal operation, which is 99% of the usage. There may also be sensors that are event driven which report change in state, such as door open/closed, door locked/unlocked, switch on/off, etc. This is also low duty cycle.

Occasionally there is an event, maybe an emergency, where the central monitoring system must get readings from all sensors as soon as possible. The central controller must send a request to all sensors to report their current measurement or state. This requires a low latency response mechanism that can maintain long battery life.

P.1.3 LECIM behaviors

The following assumptions are essential to address the needs of LECIM applications:

- Commissioning
- Low energy
- Coverage extension

P.1.3.1 Commissioning

Commissioning by a professional installer allows the network to reduce the amount of data that must be sent by creating statefulness.

P.1.3.2 Low energy

LECIM applications require significantly low energy operation to be able to either last 20 years on original battery supply or energy harvesting mechanisms. Achieving low energy operation is made very difficult given the low data rates necessary for long range operation. Accordingly, LECIM networks must be able to elide any overhead octets not absolutely necessary to minimize transmit and receive durations, schedule link times to minimize device "on" durations, and maximize link reliability to minimize retransmissions.

P.1.3.3 Coverage extension

To keep infrastructure costs to a minimum, LECIM devices have large link margins to achieve long ranges without requiring mesh devices or repeater devices. Requiring mesh or repeater devices would increase the number of devices needed to sustain the network, increase costs by requiring renting or leasing space for those devices, and in most cases require mains power for these devices.

P.2 Functionality added: DSSS, FSK, fragmentation, frame priority, PIBs, IEs, attributes

P.2.1 DSSS

The DSSS devices used by LECIM networks differ from the other DSSS devices defined in this standard in that they have significant process gain to allow devices to receive messages with very low or negative carrier to noise ratios. High process gain also allows for code division multiple access (CDMA) operation to reduce the possibility of collisions.

P.2.2 FSK

The FSK devices for LECIM are typically narrow bandwidth (hence low data rate) devices that enable high sensitivities and many channels in order to reduce the possibility of collisions.

P.2.3 Fragmentation

The lower effective data rates resulting from high processing gain or narrow bandwidths dramatically decrease data rate, hence an increase in the bit times. The increase in bit times would make typical IEEE 802.15.4 frames so long in duration as to decrease their reliability and degrade coexistence. To keep each transmission duration sufficiently short, a method of fragmentation at the PHY/MAC level is required. The properties of this fragmentation method are to reduce all overhead to the minimum amount, by preconfiguring the link between two devices with the information necessary for reception and proper reassembly. This preconfiguration is done in order to eliminate the need to send this information in every packet.

P.2.4 Frame priority

Frame priority allows LECIM networks to exhibit low latencies for truly critical data messages versus those latencies for link maintenance or other lower priority messages.

P.2.5 PIB attributes

LECIM mechanisms and protocols require additional PIB attributes.