The PACTOR-III Protocol

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1. Introduction

Similar to PACTOR-I and -II, PACTOR-III is also a half-duplex synchronous ARQ system. In the standard mode, the initial link setup is still performed using the FSK (PACTOR-I) protocol, in order to achieve compatibility to the previous systems. If both stations are capable of PACTOR-III, automatic switching to this highest protocol level is performed.

While PACTOR-I and -II were developed for operation within a bandwidth of 500 Hz, PACTOR-III is designed specifically for the commercial market to provide higher throughput and improved robustness utilizing a complete SSB channel. A maximum of 18 tones spaced at 120 Hz is used in optimum propagation conditions. The highest raw bit rate transferred on the physical protocol layer is 3600 bits/second, corresponding to a net user data rate of 2722.1 bits/second without compression. As different kinds of online data compression are provided, the effective maximum throughput depends on the transferred information, but typically exceeds 5000 bits/second, which is more than 4 times faster than PACTOR-II. At the low SNR edge, PACTOR-III also achieves a higher robustness compared to PACTOR-II.

The ITU emission designator for PACTOR-III is 2K20J2D.

2. Speed Levels and Bandwidth

Depending on the propagation conditions, PACTOR-III utilizes 6 different speed levels (SL), which can be considered as independent sub-protocols with distinct modulation and channel coding. The physical data rate on all speed levels is 100 baud. Up to 18 tones are used, spaced at 120 Hz. The maximum occupied bandwidth is 2.2 kHz (from 400 to 2600 Hz). The center frequency of the entire signal is 1500 Hz. The tone representing the "lowest" channel is sent at a frequency of 480 Hz, the highest tone is 2520 Hz. As tones are skipped on the two lowest speed levels, the gaps between them increase to N times 120 Hz in these cases. The following table illustrates the number and position of the used channels in the different speed levels.

	CN	0	1	2	3	4	5	6	7	8	9	10	11	12	12	14	15	16	17
SL																			
1							x							x					
2					x		x		x			x		x		x			
3				x	x	x	x	x	x	x	x	x	x	x	x	x	x		
4				x	x	x	x	x	x	x	x	x	x	x	x	x	x		
5			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
6		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	TF	480	600	720	840	960	1080	1200	1320	1440	1560	1680	1800	1920	2040	2160	2280	2400	2520

SL = speed level, CN = channel number, TF = tone frequency [Hz], an "x" indicates that the tone is used in the respective SL

Similar to the PACTOR-II protocol, the digital data stream that constitutes a specific virtual carrier is swapped to a different tone with every ARQ cycle in order to increase the diversity gain by adding additional frequency diversity. Considering that in the normal state the numbers of the virtual data carriers correspond with the numbers of the respective tones, the swapped mode assigns carrier 0 with tone 17, 1 with 16, 2 with 9, 3 with 10, 4 with 11, 5 with 12, 6 with 13, 7 with 14 and 8 with 15. Tones 5 and 12 can be considered as equivalent to the two carriers of PACTOR-II, as they transfer the variable packet headers and the control signals (see below).

3. Modulation, Coding and Data Rates

As modulation, either Differential Binary Phase Shift Keying (DBPSK) or Differential Quadrature Phase Shift Keying (DQPSK) is applied. After full-frame bit-interleaving of the entire data packet, an optimum rate 1/2 convolutional code with a constraint length (CL) of 7 or 9 is used. Similar to the PACTOR-II protocol, the codes with higher rates, i.e. rate 3/4 and rate 8/9, are derived from that code by so-called puncturing: Prior to the transmission, certain of the symbols of the rate 1/2 encoded stream are “punctured”, i.e. deleted and thus not transmitted. At the receiving side, the punctured encoded bits are replaced with “null” symbols prior to decoding with the rate 1/2 decoder. The decoder treats these null symbols neither as a received “1” nor as “0”, but as an exactly intermediate value. No information is thus conveyed by that symbol that may influence the decoding process. The coding performance of “punctured” code operation nearly matches the coding performance of the best known classic rate 3/4 or 8/9 codes with a comparable constraint length, provided that the puncture pattern is chosen carefully. The major advantage of this approach is that a single code rate decoder (in our case a rate 1/2 decoder) can implement a wide range of codes. In the SCS modems, a real Viterbi decoder with soft decision is utilized for all speed levels, providing a maximum of coding gain.

The following table shows the modulation, the constraint length (CL) and the code rate (CR) of the applied convolutional code, the physical data rate (PDR), i.e. the raw bit rate transferred on the physical protocol layer, the net data rate (NDR), i.e. the uncompressed user data rate, as well as the crest factor (CFR) of the signal in the different speed levels (SL).

SL	Modulation	CL	CR	PDR	NDR	CFR
1	DBPSK	9	1/2	200	76.8	1.9
2	DBPSK	7	1/2	600	247.5	2.6
3	DBPSK	7	1/2	1400	588.8	3.1
4	DQPSK	7	1/2	2800	1186.1	3.8
5	DQPSK	7	3/4	3200	2039.5	5.2
6	DQPSK	7	8/9	3600	2722.1	5.7

SL = speed level, CL = constraint length, CR = code rate, PDR = physical data rate, NDR = net data rate, CFR = crest factor (dB)

3. Cycle Duration

The ARQ cycle durations are still 1.25 seconds (short cycles) and 3.75 seconds (data mode), which is one of the requirements to obtain easy compatibility to the previous PACTOR standards. Due to signal propagation and equipment switching delays, PACTOR-III, similar to the preceding PACTOR protocols, has in this standard mode a maximum range for ARQ contacts of around 20,000 km. Therefore, a long path option is again available, enabling contacts up to 40,000 km, with cycle times of 1.4 seconds (short cycles) and 4.2 seconds (data mode), respectively. The sending station initiates a connect in 'Long Path Mode' by inverting the first byte of the callsign in the FSK connect frame (for details, see the PACTOR-I protocol description).

4. Structure of Packets and Control Signals

Except from different data field lengths, the basic PACTOR-III packet structure is similar to the previous PACTOR modes. It consists of a packet header, a variable data field, the status byte and the CRC. Two types of headers are used: Sixteen “variable packet headers” consisting of 8 symbols each are sent alternately on tones 5 and 12 to code 4 bit of information: Bit 0 defines the request-status indicating a repeated packet. Bits 2 and 3 specify the speed levels 1 to 4 according to the modulo-4 logic, whereas the detection of levels 5 and 6 is performed by additionally analyzing the constant packet headers. Bit 4 gives the current cycle duration: “0” specifies short and “1” long cycles. The following table shows the hexadecimal codes of the variable packet headers.

Definitions of the Variable Packet Headers (initiating tones 5 and 12)							
VH0	0x1873174f	VH1	0xfc0f6047	VH2	0x0a4c7ea7	VH3	0x09bce11f
VH4	0x8e67c43c	VH5	0x7268a47b	VH6	0x842bba9b	VH7	0x87db2523
VH8	0x4d55aa6a	VH9	0xb15aca2d	VH10	0x4719d4cd	VH11	0x44e94b75
VH12	0x3ccd91a9	VH13	0xc0c2f1ee	VH14	0x3681ef0e	VH15	0x357170b6

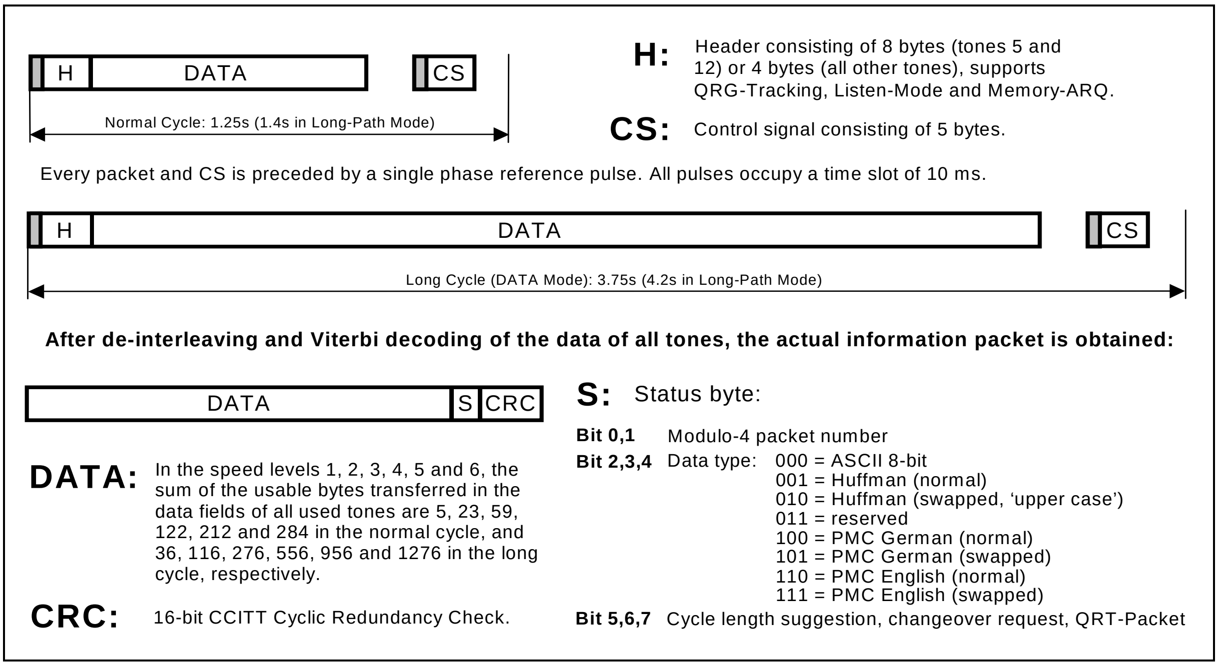
The remaining tones 1-4, 6-11 and 13-18 are preceded by constant headers that characterize the respective tones without transferring any additional information. They support QRG tracking, Memory-ARQ, the Listen-Mode and the detection of the speed levels 5 and 6. The table below presents the hexadecimal codes of the constant packet headers.

Definitions of the Constant Packet Headers (initiating tones 1-4, 6-11, 13-18)							
CH0	0xc324	CH1	0xf987	CH2	0xb1c8	CH3	0xf370
CH4	0x801d	CH5	0x7c3d	CH6	0xd8f1	CH7	0x5a3c
CH8	0x792d	CH9	0x8397	CH10	0x33aa	CH11	0x5a3c
CH12	0x823c	CH13	0x073f	CH14	0xf798	CH15	0xd801

The headers are followed by the data fields that transfer the user information. On the 6 different speed levels, 5, 23, 59, 122, 212 and 284 usable bytes are transferred in the short cycle and 36, 116, 276, 556, 956 and 1276 in the long cycle, respectively. After de-interleaving and decoding of the entire data transferred on all tones within a certain cycle, the actual information packet is obtained, which consists of the user data, a status byte and the 2 CRC bytes. The status byte characterizes the packet by a two-bit packet counter to detect repetitions (bit 0 and 1), provides information on the applied data compression (bits 2, 3 and 4), suggests to switch to the data mode when the amount of characters in the transmit buffer exceeds a certain number (bit 5), indicates a changeover request (bit 6) and initiates the QRT protocol (bit 7). For details, see the graphic below. The final part of the packet is a 16-bit CRC calculated according to the CCITT-CRC16 standard.

PACTOR-III uses the same set of six 20-bit Control Signals (CS) as PACTOR-II. They are transmitted simultaneously on the tones 5 and 12 and all have the maximum possible mutual hamming distance to each other. Hence they reach exactly the Plotkin boundary and represent a perfect code. This allows the advantageous use of the Cross Correlation method for decoding, a kind of soft decision that leads to the correct detection of even inaudible CS. CS1 and CS2 are used to acknowledge/request packets and CS3 forces a break-in. CS4 and CS5 handle the speed changes: CS4 demands an increase of the speed to the next higher level. CS5 acts as a NACK asking for a repetition of the previously sent packet and at the same time for a reduction of the speed to the next lower level. CS6 is a toggle for the packet length and inquires a change to long cycles in case that the actual state is short cycles and vice versa. All CS are always sent in DBPSK in order to obtain maximum robustness.

The graphic below illustrates the entire PACTOR-III cycle.



H: Header consisting of 8 bytes (tones 5 and 12) or 4 bytes (all other tones), supports QRG-Tracking, Listen-Mode and Memory-ARQ.

CS: Control signal consisting of 5 bytes.

Every packet and CS is preceded by a single phase reference pulse. All pulses occupy a time slot of 10 ms.

After de-interleaving and Viterbi decoding of the data of all tones, the actual information packet is obtained:

DATA: In the speed levels 1, 2, 3, 4, 5 and 6, the sum of the usable bytes transferred in the data fields of all used tones are 5, 23, 59, 122, 212 and 284 in the normal cycle, and 36, 116, 276, 556, 956 and 1276 in the long cycle, respectively.

CRC: 16-bit CCITT Cyclic Redundancy Check.

S: Status byte:

Bit 0,1 Modulo-4 packet number
Bit 2,3,4 Data type: 000 = ASCII 8-bit
001 = Huffman (normal)
010 = Huffman (swapped, ‘upper case’)
011 = reserved
100 = PMC German (normal)
101 = PMC German (swapped)
110 = PMC English (normal)
111 = PMC English (swapped)
Bit 5,6,7 Cycle length suggestion, changeover request, QRT-Packet

5. On-line Data Compression

Like in the previous PACTOR modes, automatic on-line data compression is also applied in the PACTOR-III protocol, comprising Huffman and run-length encoding as well as Pseudo-Markov Compression (PMC, see below). The information sending system automatically checks, whether one of those or the original ASCII code leads to the shortest data package, which depends on the probability of occurrence of the characters. There is hence no risk of losing throughput capacity. Of course PACTOR-III is still able to transfer any given binary information, e.g. programs or picture- and voice files. In case of binary data transfer, the on-line data compression normally switches off automatically due to the character distribution. An external data compression in the terminal program is usually performed instead.

Huffman compression exploits the “one-dimensional” probability distribution of the characters in plain texts. The more frequently a character occurs, the shorter has to be its Huffman symbol. More details including the code table used in the PACTOR protocols can be found in the description of the PACTOR-I standard.

Markov compression can be considered as a “double” Huffman compression, since it not only makes use of the simple probability distribution, but of the “two-dimensional” probability. For each preceding character, a probability distribution of the very next character can be calculated. For example, if the actual character is “e”, it is very likely that “i” or “s” occurs next, but extremely unlikely that an “X” follows. The resulting probability distributions are much sharper than the simple one-dimensional distribution and thus lead to a considerably better compression. Unfortunately, there are two drawbacks: Since for each ASCII character a separate coding table is required, the entire Markov coding table becomes impractically large. Additionally, the two-dimensional distribution and thus also the achievable compression factor depends much more on the kind of text than the simple character distribution. We have therefore chosen a slightly modified approach which we called Pseudo-Markov Compression (PMC), because it can be considered as a hybrid between Markov- and Huffman encoding. In this variant, the Markov encoding is limited to the 16 most frequent “preceding” characters. All other characters trigger normal Huffman compression of the very next character. This reduces the Markov coding table to a reasonable size and also makes the character probabilities less critical, since especially the less frequent characters tend to have unstable probability distributions. Nevertheless, for optimum compression, two different tables for English and German texts are defined in the PACTOR-II and -III protocols and automatically chosen. When transferring plain text, PMC yields a compression factor of around 1.9 compared to 8-bit ASCII.

Run-length encoding allows the effective compression of longer sequences of identical bytes. The special prefix byte “0x1D” is defined, which initiates the 3 byte run length code. The second byte is called the “code byte” and contains the original code of the transferred byte within the range of the entire ASCII character set. The third byte provides the number of code bytes to be displayed on the receiving side within the range between “0x01” to “0x60”. Values between “0x00” and “0x1f” are transferred as “0x60” to “0x7f”, values between “0x20” and “0x60” are transferred without any change. If, for example, the sequence “AAAAAAAA” should be transferred, the respective 3 byte run-length code would be “0x1D 0x41 0x68”.

6. Signal Characteristics and Practical Considerations

As the FSK PACTOR standard is used for the initial link establishment, frequency deviations of the connecting stations of up to +/–80 Hz are still tolerated. Similar to the PACTOR-II mode, a powerful tracking algorithm is provided in the SCS modems to compensate any divergence and exactly match the signals when switching to the DPSK mode, which requires a high frequency accuracy and stability.

The PACTOR-III signal provides a very high slope steepness in order to avoid any spillover in adjacent channels. Therefore, low quality audio filters may lead to a distortion of the side tones of the signal on the higher speed levels on the transmitting as well as on the receiving side. To partly compensate for that, SCS modems allow the amplitude of the signal edges to be enhanced individually in two steps using the “Equalize” command, which defines the function of the PACTOR-III transmit equalizer. A value of “0” switches this function off, “1” means a moderate, and “2” a strong enhancement of the side tones of the signal.

Further, it has to be taken into consideration, that, due to the different possible “tones” settings relating to the FSK mode used for the initial link setup, a shift of the center frequency of the signal may occur with the automatic switching to PACTOR-III. Therefore, the “tones” settings should be checked carefully and adapted to the other stations in the network in order to make sure that no offset occurs between the linked stations and the PACTOR-III signal is placed symmetrically within the filter bandwidth. Usually, identical “tones” settings on both sides of a PACTOR-III link are required for proper operation. SCS recommends to set “tones” to “4”, defining the FSK connect tones as 1400 and 1600 Hz, which are balanced around the PACTOR-III center frequency of 1500 Hz, to avoid incompatibilities between PACTOR-III users.

The following figure shows a spectrum of the PACTOR-III signal on speed level 6 with all 18 tones.