The PACTOR-3 Protocol

A Technical Description

The PACTOR-3 Protocol

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1. Introduction

Similar to PACTOR-1 and -2, PACTOR-3 is a half-duplex synchronous ARQ system. In the standard mode, the initial link setup is performed using the FSK (PACTOR-1) protocol, in order to achieve compatibility to the previous systems. If both stations are capable of PACTOR-3, automatic switching to this highest protocol level is performed.

While PACTOR-1 and -2 were developed for operation within a bandwidth of 500 Hz, PACTOR-3 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 data 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-2. At low SNR, PACTOR-3 achieves a higher robustness compared to PACTOR-2.

The ITU emission designator for PACTOR-3 is 2K20J2D.

2. Speed Levels and Bandwidth

Depending on the propagation conditions, PACTOR-3 utilizes 6 different speed levels (SL), which can be considered as independent sub-protocols with distinct modulation and channel coding. The symbol rate is 100 baud on all speed levels. 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. Figure 1 illustrates the number and position of the used channels at the different speed levels.

Similar to the PACTOR-2 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-2, 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-2 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 bits of the rate 1/2 encoded bit stream are “punctured”, i.e. deleted and thus not transmitted. At the receiving side, the punctured bits are replaced with “null” bits prior to decoding with the rate

	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

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

Figure 1: Number and position of the used channels at the different speed levels (SL)

1/2 decoder. The decoder treats these null bits neither as a “1” nor as “0”, but as an exactly intermediate value. Thus, these bits have no influence on the decoding process. The coding gain of a “punctured” code nearly matches the coding gain of the best known specific 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. Therefore, punctured codes are used in many modern communication systems. In the SCS modems, a Viterbi decoder with soft decision is used for all speed levels, yielding a maximum of coding gain.

Figure 2 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 (CF) of the signal for the different speed levels (SL).

The following two figures show the bit error rates (BER) for the different speed levels. In figure 3, the rates are referenced to the normalized energy per bit (E_b/N_0). Due to the different number of tones (2-18) and the different modulations (DBPSK/DQPSK), this figure does not reveal the performance with respect to the channel SNR. Thus, in figure 4, the rates are referenced to the channel SNR at a channel bandwidth (BW) of 3 kHz. The different speed levels cover a wide SNR range. For maximum throughput with SL6, a channel SNR of 14 dB is required.

It should be noted, that the performance in terms of throughput in bits per second depends on

SL	Modulation	CL	CR	PDR	NDR	CF
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

CL = constraint length, CR = code rate, PDR = physical data rate, NDR = net data rate, CF = crest factor (dB)

Figure 2: Parameters of the different speed levels (SL)

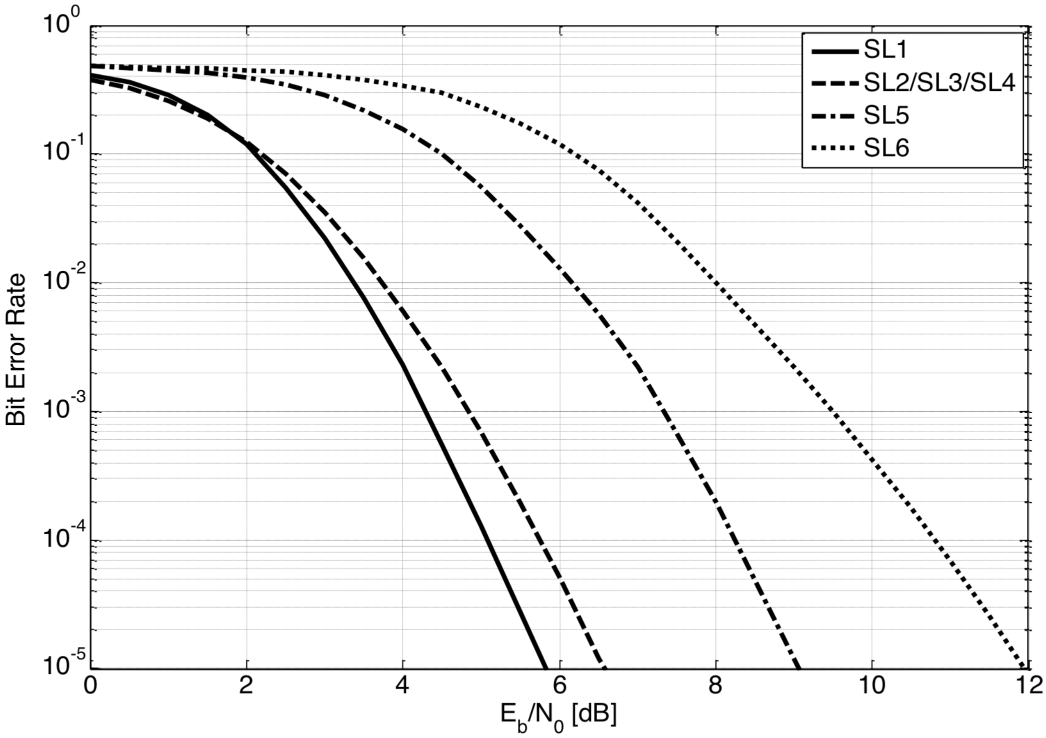


Figure 3: Bit error rate for the different speed levels (SL) with respect to the energy per bit

the implementation of the ARQ protocol and cannot be deduced from the physical data rates and the bit error rates. Performance measurements will be presented below.

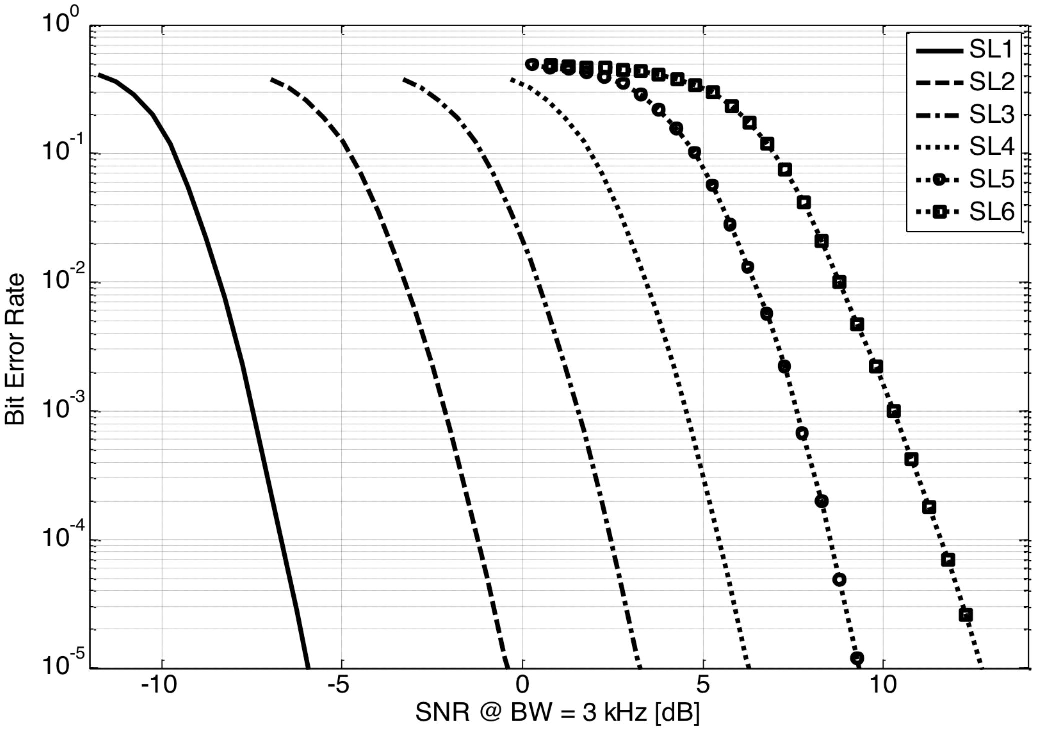


Figure 4: Bit error rate for the different speed levels with respect to the channel SNR

4. Crest Factor and Transmitter Output Power

One of the most important characteristics of the PACTOR-3 signal is the low crest factor (CF), especially with the lower speed levels. As most HF power amplifiers are peak-power limited and use a peak-power automatic level control (ALC), PACTOR-3 provides considerably more transmitter output power than comparable multicarrier modes like, for example, OFDM modes when using the same power amplifier, thereby increasing the SNR at the receiver. Up to SL4, the CF fairly compares to the CF of single-carrier modes. Even with SL5 and SL6, the CF is about 3 dB lower than the CF of typical OFDM modes, thereby doubling the transmitted RMS power. In the context of Digital Radio Mondiale (DRM), it has been found that single-carrier modes perform much better than OFDM modes if the coding is weak (rate > 2/3); OFDM modes without coding are well known to be a disaster when used over highly frequency selective channels. With strong coding (rate <= 1/2), OFDM modes perform slightly better than single-carrier modes. These results are based on two assumptions: (a) the transmitted RMS power is the same for both modes, meaning that the peak power of the OFDM mode is several dB's higher than that of the single-carrier mode; (b) an optimum DFE equalizer is used with the single-carrier mode (Remark: an optimum MLSE equalizer cannot be used because the channel impulse response is too long). If the peak power is held constant, the single-carrier mode performs better for all reasonable coding rates, but the required optimum DFE equalizer presents an inevitable obstacle. PACTOR-3 is designed to provide the benefits of both modes by minimizing the CF and avoiding the use of an equalizer.

SCS modems operate with constant peak power at all speed levels to optimally exploit the available output power of peak-power limited HF power amplifiers. Thus, the RMS output power changes when switching through the speed levels, due to the different CF's. The channel SNR at the receiver changes accordingly. This has to be kept in mind when interpreting the bit error rates in figure 4.

5. Cycle Duration

In the standard mode, the ARQ cycle durations are 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. In this mode, due to signal propagation and equipment switching delays, PACTOR-3 is capable to establish ARQ links over a maximum distance of around 20,000 km. To further extend the maximum distance, a 'Long Path Mode' is available, enabling ARQ links up to a maximum distance of 40,000 km, with cycle times of 1.4 seconds (short cycles) and 4.2 seconds (data mode), respectively. The calling station initiates a link in 'Long Path Mode' by inverting the first byte of the callsign in the FSK connection frame (for details, see the PACTOR-1 protocol description).

6. Structure of Packets and Control Signals

Except from different data field lengths, the basic PACTOR-3 packet structure is similar to the previous PACTOR modes. It consists of a packet header, a variable data field, a status byte and a 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 bits 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 a 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"

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

Figure 5: Definitions of the Variable Packet Headers (initiating tones 5 and 12)

specifies short and "1" data cycles. Figure 5 shows the hexadecimal codes of the variable packet headers.

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 frequency tracking, memory-ARQ, the Listen-Mode and the detection of the speed levels 5 and 6. Figure 6 presents the hexadecimal codes of the constant packet headers.

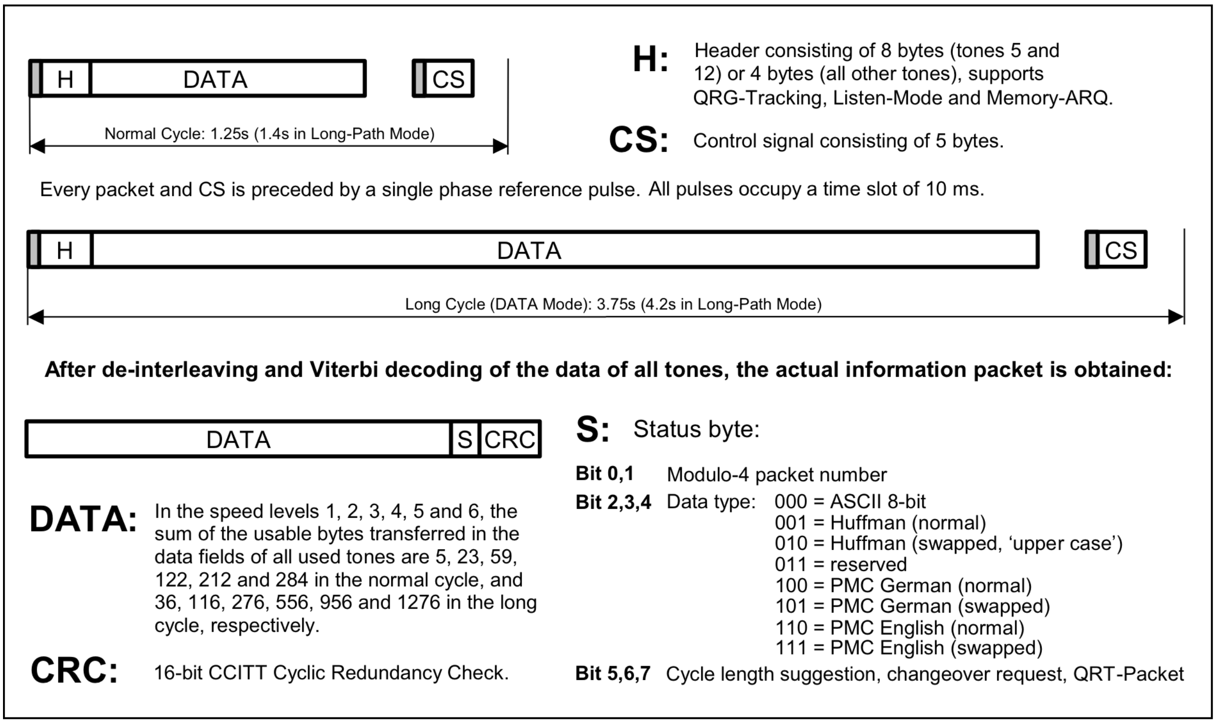
The headers are followed by the data fields that transfer the user information. On the 6 different speed levels, 5, 23, 59, 122, 212, and 284 payload bytes are transferred in the short cycle and 36, 116, 276, 556, 956, and 1276 payload bytes in the long cycle, respectively. After de-interleaving and 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 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 link termination 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-3 uses the same set of six 20-bit Control Signals (CS) as PACTOR-2. 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 use of the Cross Correlation method for CS detection, a kind of soft decision that leads to the correct detection of even inaudible CS, due to the high correlation gain. 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.

Figure 7 illustrates the PACTOR-3 ARQ operation.

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

Figure 6: Definitions of the Constant Packet Headers (initiating tones 1-4, 6-11, 13-18)



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:

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

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.

Figure 7: PACTOR-3 ARQ operation

7. On-line Data Compression

Like in the previous PACTOR modes, automatic on-line data compression is also applied in the PACTOR-3 protocol, comprising Huffman and run-length encoding as well as Pseudo-Markov Compression (PMC, see below). The information sending system (ISS) automatically checks, whether one of these compression modes or the original ASCII code leads to the shortest data package, which depends on the probability of occurrence of the characters. Hence, there is no risk of losing throughput capacity. Of course, PACTOR-3 is still capable to transfer any given binary information, e.g. programs or picture and voice files. In case of a 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 its Huffman symbol has to be. More details including the code table used in the PACTOR protocols can be found in the description of the PACTOR-1 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 more concentrated 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 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 PMC, 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-2 and -3 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 a 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. For example, the sequence "AAAAAAAA" is transferred using the 3 byte run-length code "0x1D 0x41 0x68".

8. 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-2 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-3 signal provides a very high spectral steepness in order to avoid any spillover in adjacent channels. Therefore, low quality audio filters may cause distortion of the side tones of the higher speed levels, both on the transmitting and 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-3 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 related 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-3. 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-3 signal is placed symmetrically within the filter bandwidth. Usually, identical "tones" settings on both sides of a PACTOR-3 link are required for proper operation. SCS recommends to set "tones" to "4", defining the FSK connection tones as 1400 and 1600 Hz, which are balanced around the PACTOR-3 center frequency of 1500 Hz, to avoid incompatibilities between PACTOR-3 users.

Figure 8 shows the spectrum of a PACTOR-3 signal at speed level 6 with all 18 tones active.

9. Performance measurements

The performance of ARQ modes with different speed levels critically depends on the implementation of the ARQ protocol and the automatic selection of an appropriate speed level

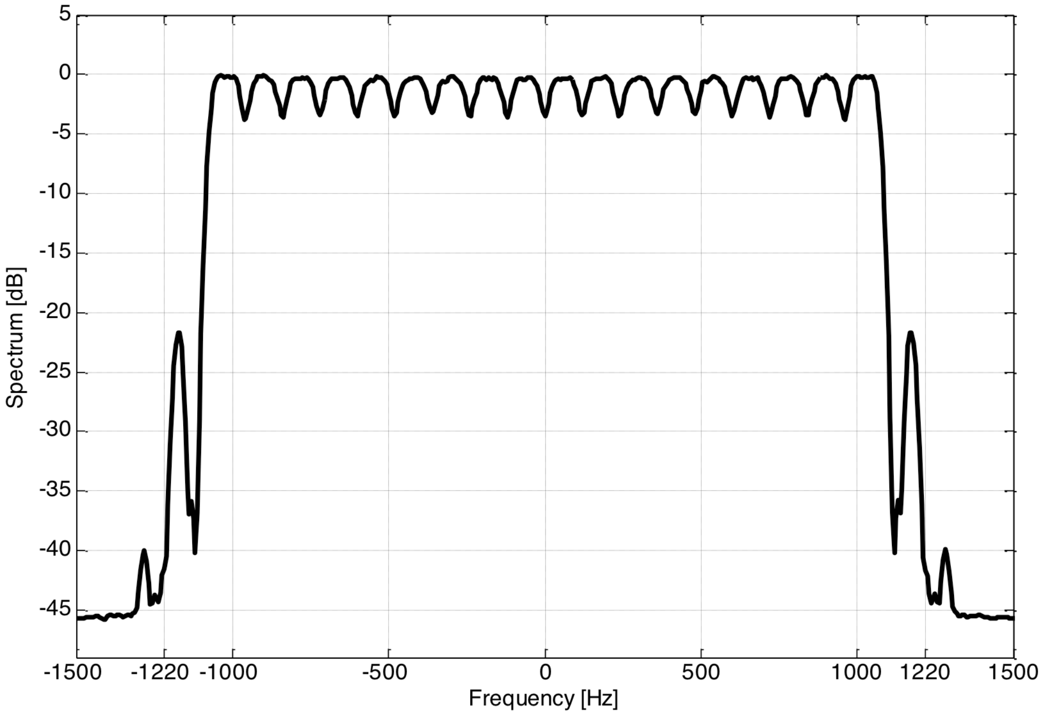


Figure 8: Spectrum of a PACTOR-3 signal at speed level 6 (SL6) with all 18 tones active

for the given channel conditions. PACTOR-3 comprises memory-ARQ to smooth the transitions between speed levels and to improve the throughput at low SNR's. In memory-ARQ, the combination of re-transmitted data packets allows for safe data transmission over extremely bad channels even if each received packet is corrupted. Figure 9 presents the results of throughput measurements over an additive white gaussian noise channel (AWGN) and an ITU-R F.420 poor channel. The SNR is evaluated with respect to the RMS output power at speed level 1 (SL1) to correct for the different CF's. Due to the bit error rates presented in figure 4, the maximum throughput of 2720 bps should be achieved with SL6 at a channel SNR of more than 14 dB with respect to the RMS output power at SL6. According to figure 2, the CF's of SL1 and SL6 differ by 3.8 dB. Therefore, the maximum throughput should be achieved at a channel SNR of more than 18 dB with respect to the output power at SL1 which fairly agrees with the measured AWGN throughput in Figure 9.

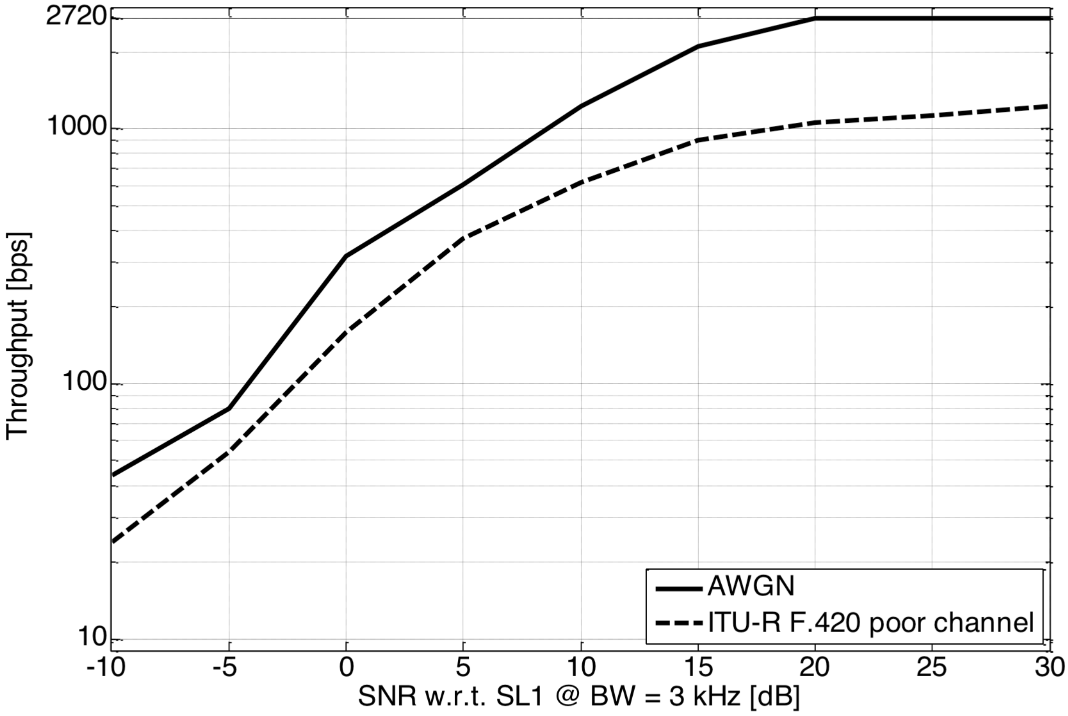


Figure 9: Throughput of PACTOR-3

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