PACTOR-II

The new Dimension in Data Transmission Technology

By Dr. Tom Rink, DL2FAK, and Hans-Peter Helfert, DL6MAA

Part 1: Short Description of the PACTOR-II Protocol

I. Introduction

All new modes should provide significant improvements over existing systems, which must not only refer to the maximum throughput and the robustness. Other basic attributes, like signal bandwidth, required frequency accuracy and compatibility to existing standards also have to be taken into consideration.
Modulation and encoding methods that supply high throughput rates, e.g. 16-DPSK, normally suffer from a lack of robustness. On the other hand, systems distinguished by a high robustness, e.g. DBPSK combined with a rate 1/2 convolutional code, only provide a low maximum throughput. Therefore adaptive digital modes have to be used, that apply different modulation and encoding methods depending on the channel quality. Just changing the symbol rate however, leads to only little adaptivity and additionally results in variations of the bandwidth. In order to prevent any spillover in adjacent channels, the bandwidth should ideally always remain the same, regardless of whether a robust or a fast data transmission is performed. As 500 Hz CW filters are very commonly used and due to the usual spacing of the mailbox frequencies on short wave, a maximum bandwidth of 500 Hz should not be exceeded. In addition, there should not be too high a demand placed on the transceiver used, regarding its frequency adjustment and stability. For optimum results, maximum frequency deviations similar to FSK modes should be tolerated. This forces the use of powerful tracking methods, which allow a link also to be established if the deviation is up to +/- 80 Hz. Further, a new mode should be backwards compatible to an existing standard, preferably with automatic switching, in order to prevent a deficiency of QSO partners in the early stage.
PACTOR-II meets all the above mentioned requirements. It is fully backwards compatible with the current PACTOR standard, as the initial link setup is still done in FSK. If both stations are capable of Level II, an automatic switching is performed. The PACTOR-II protocol basically uses a two-tone DPSK system with raised cosine pulse shaping, which reduces the required bandwidth to less than 500 Hz. The maximum absolute transfer rate is 800 bits per second. Due to the improved on-line data compression, maximum effective throughput rates of more than 1200 bits per second can be obtained. PACTOR-II is thus the fastest short wave digital mode. Very efficient error control coding using a convolutional code with a constraint length of 9 and a real Viterbi decoder with soft decision is applied at all speed levels, in addition to analog Memory-ARQ. PACTOR-II is also therefore, by far the most robust digital mode, which allows a link to be established and achieve a reasonable throughput in such poor propagation conditions that all other modes fail. In comparison with the current FSK PACTOR standard including analog Memory-ARQ, which had been the most robust digital mode until the release of PACTOR-II, a further gain of robustness of around 8 dB could be obtained. The following chapters describe some details of the PACTOR-II protocol.

II. Structure and Timing of the PACTOR-II Frames

Similar to the current FSK PACTOR standard, PACTOR-II is also a half-duplex synchronous ARQ system without any mark/space convention. It may thus be operated in USB as well as LSB position of the transceiver. The initial link setup is still performed using the FSK (PACTOR-I) protocol, in order to achieve compatibility to the previous level. If both stations are capable of PACTOR-II, an automatic switching to the higher level is performed. The basic PACTOR-II frame structure is similar to PACTOR-I. It consists of a header, a variable data field, the status byte and the CRC. The standard cycle duration does not differ from FSK PACTOR and is still 1.25 seconds, which is one of the requirements to obtain easy compatibility to Level I. Longer Control Signals (CS) had to be applied to achieve a higher robustness for the acknowledgment signal, required due to the greater robustness of the data channel. The entire length of the standard packet had to be shortened to 0.8 seconds in order not to shorten the maximum possible propagation delay, which is thus still 170 milliseconds. The requirements to operate PACTOR-II regarding the transmit delay and the receiver recovery time of the used equipment therefore remain unchanged in comparison with Level I.

Due to the signal propagation delay, and equipment switching delays, PACTOR-II as well as PACTOR-I has in the standard mode a maximum range for ARQ contacts of around 20,000 km. As with PACTOR-I, a long path option is available also for PACTOR-II, enabling contacts up to 40,000 km. The sending station calls the partner station in 'Long Path Mode'. Initial contact is established using the PACTOR-I FSK protocol as previously mentioned, but with a cycle time of 1.4 seconds instead of 1.25. This longer cycle time allows for the much greater propagation delays found on 'Long Path' contacts. The link then automatically switches to PACTOR-II, with the same cycle duration. In the new data mode (see below), timing is also automatically adjusted to obtain longer receiving gaps.
Unlike the previous level, PACTOR-II additionally switches to longer packets if the data blocks are not filled up with idles, (i.e. if the transmitter buffer indicates that more information has to be transferred than fitting into the standard packets). If the information sending station (ISS) prefers to use long packets, it sets the long cycle flag in the status word. The information receiving station (IRS) then finally can accept the proposed change of the cycle duration by sending a CS6. This situation, for example, occurs when reading longer files out of mailboxes. The long packets are basically made up like the short ones, but consist of a larger data field, which may contain up to 2208 bits of usable information. The length of these data packets is 3.28 seconds, which leads to an entire cycle duration of 3.75 seconds in this so-called data mode. Figure 1 shows the PACTOR-II cycle duration and the packet construction in the standard mode as well as in the data mode.
When entering text manually in QSO traffic from operator to operator, the maximum throughput of the standard mode is normally not used up, thus the required higher flexibility of the system is still available due to the short packets. The efficient use of longer data packets on short wave is generally only possible, if powerful error control coding, with full frame interleaving is applied to cancel out error bursts or short fading periods. As already mentioned, PACTOR-II uses a convolutional code with a constraint length of 9, a real Viterbi decoder and soft decision, in addition to analog Memory-ARQ. Due to the high coding gain and the resulting capacity of error correction without requesting a repetition of the entire packet, a significant increase in the effective throughput could be obtained. Proceeding from average bit error rates on short wave channels, simple block codes are usually unable to provide enough coding gain. This often leads to a decrease in speed when using longer data strings, as repetitions often cannot be avoided.

PACTOR-II uses six different CS, each consisting of 40 bits, all having exactly the maximum possible mutual hamming distance of 24 bits to each other. They thus reach exactly the Plotkin boundary and also represent a perfect code. This allows the advantageous use of the Cross Correlation method for decoding, which is also a kind of soft decision, leading to the correct detection of even inaudible CS. This checking is not only confined to a simple binary principle. A complex analog test procedure is applied, using the fine detail data from the DSP, to evaluate the single CS received, as well as the information summed up in the Memory-ARQ buffer. Similar to Level I, CS1 and CS2 are used to acknowledge/request packets and CS3 forces a break-in. CS4 and CS5 handle the speed changes, and CS6 is a toggle for the packet length. All CS are always sent in DBPSK in order to obtain a maximum of robustness.

III. Speed Levels and Error Control Coding

As mentioned in the introduction, PACTOR-II uses a two-tone DPSK modulation system. Due to the raised cosine pulse shaping, the maximum required bandwidth is only around 450 Hz at minus 50 dB. ASK, which was also tested in the early stage, provided poorer results in weak conditions compared with a higher DPSK modulation, as different amplitude levels are more difficult to distinguish in noisy channels than more phase levels. Additionally, ASK increases the Crest Factor of the signal. For these reasons, it is not used in the final PACTOR-II protocol. Basic information on these items can also be found in the first part of this series.
PACTOR-II uses instead, different DPSK modulation schemes and various code rates. The Crest Factor of the PACTOR-II signal is therefore only 1.45. The basic code used is an optimum rate 1/2 convolutional code with a constraint length of 9. Codes with higher rates, e.g. rate 2/3 and rate 7/8, can be 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' or deleted, and not transmitted. At the receiving end, 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 2/3 or 7/8 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 PTC-II, the Viterbi algorithm is implemented for decoding of the convolutional code. Nevertheless, there are several different methods to decode the PACTOR-II signal, which require less processing power, but in return for this, also provide less coding gain. However, these methods at least allow compatibility to the PACTOR-II standard and may therefore be applied in cheaper hardware.
The most robust PACTOR-II speed level employs DBPSK with rate 1/2 coding, which per cycle allows an absolute throughput of 5 bytes in the standard mode and 36 bytes in the data mode respectively. In the next step, DQPSK with rate 1/2 coding is applied, which leads to an absolute throughput of 14 bytes in the standard mode and 76 bytes in the data mode. This is followed by 8-DPSK with a rate 2/3 coding, providing a throughput of 32 and 156 bytes per packet, respectively. Finally, in best propagation conditions, PACTOR-II applies 16-DPSK with a rate 7/8 coding, which allows the maximum throughput of 59 bytes in a short packet and 276 bytes in the data mode. The mentioned transfer rates are all net rates referring to 8-bit ASCII, which are calculated after the error control coding and all other protocol overhead. As data compression is usually active, these throughput rates must be multiplied by the compression factor. The effective speed is therefore considerably higher in practice. All throughput rates and the corresponding modulation and encoding methods are summarized in table 1. The speed levels are automatically chosen by the PTC-II, considering the link statistics and the actual channel quality, thus no user intervention is required.

IV. On-line Data Compression

Like in the previous FSK PACTOR system, automatic on-line Huffman data compression is applied. Additionally, PACTOR-II uses run-length encoding and, as a further novelty, Pseudo-Markov Compression (PMC, see below). Compared to 8-bit ASCII (plain text) PMC yields a compression factor of around 1.9, which leads to an effective speed of about 600 bits per second in average propagation conditions in data mode. PACTOR-II is already around 3 times faster than PACTOR-I and 15 times faster than AMTOR on average channels. However, the maximum effective speed in good conditions can exceed 1200 bits per second. As the PTC-II firmware automatically checks, whether PMC, Huffman encoding or the original ASCII code is the best choice, which depends on the probability of occurrence of the characters, there is no risk of losing throughput capacity. PACTOR-II is of course still able to transfer any given binary information, e.g. programs or picture- and voice files. In these cases the on-line data compression is automatically switched off.
Ordinary 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 the Huffman symbol that is assigned to the actual character. On the other hand, 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, 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 protocol and automatically chosen by the PTC-II.

V. Some Practical Aspects

Similar to Level I, the tones of the PACTOR-II signal are spaced at 200 Hz. Their frequency may be defined freely in steps of 1 Hz by software command, as long as the shift remains 200 Hz. Thus you can easily switch between high- and low-tones, and also adjust any additionally required tone pair. This allows the utilizing of narrow CW filters in all transceivers that provide the option of activating the corresponding filters in the SSB mode.

In the PACTOR-II system, the transferred information is swapped from one channel (tone) to the other in every cycle. Unlike FSK systems, the link is thus not blocked when strong narrow band QRM completely overpowers one channel (e.g. CW or carriers), but only its maximum speed is reduced. Usual FSK systems with a mark/space convention and without Memory-ARQ have to fail in such cases, because even if a so-called 'space-only' mode is applied, the strongest signal is automatically chosen. This always leads to a break-down of the link, as the QRM is stronger than the useful signal in the proposed case.
PACTOR-II provides a comprehensive Listen-Mode, which is much more robust than known from PACTOR-I, because just the short header has to be received correctly, then the powerful error control coding can be fully utilized. Burst errors may be corrected also by monitoring stations and thus virtually do not affect the performance. The Unproto-Mode in PACTOR-II allows to choose between all the above mentioned speed and encoding levels. On the receiving side, the correct mode is detected automatically and therefore needs no user-adjustment. For example, a fast and very robust QTC mode can thus be achieved, when a message is transmitted in the Unproto-Mode using DBPSK with rate 1/2 coding.

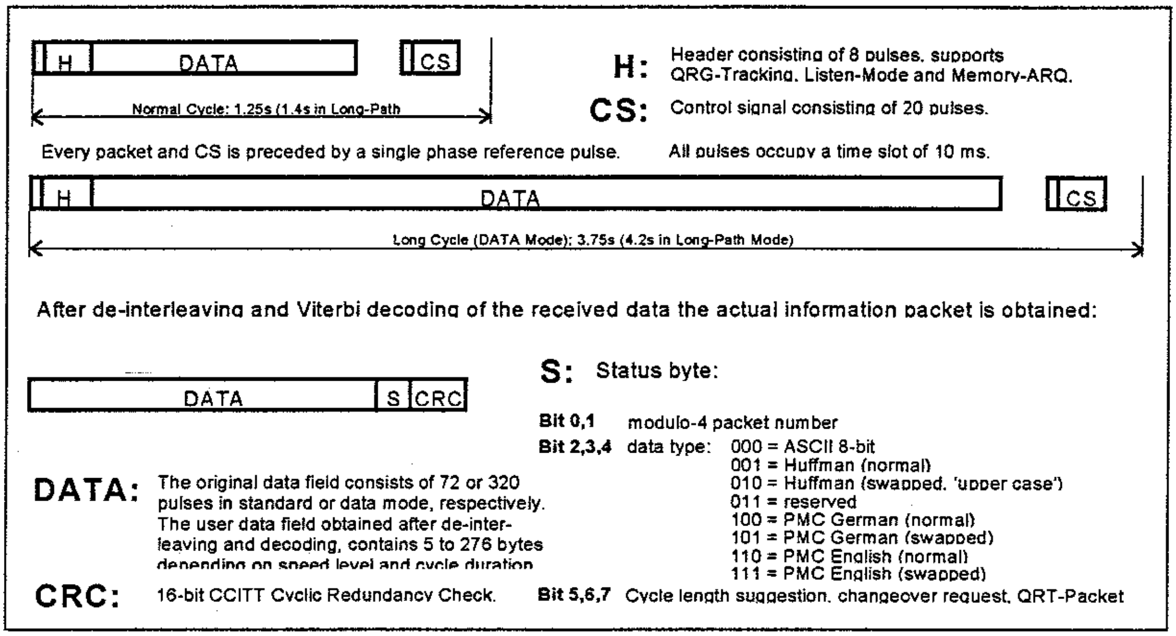

Figure 1: Structure and timing of the PACTOR-II frames

Cycle	Modulation type	Code rate	Data bytes/packet (no compression)	Data bytes/sec (with PMC, f=1.9)
standard	DBPSK	1/2	5	7.6
data	DBPSK	1/2	36	18.2
standard	DQPSK	1/2	14	21.3
data	DQPSK	1/2	76	38.5
standard	8-DPSK	2/3	32	48.6
data	8-DPSK	2/3	156	79.0
standard	16-DPSK	7/8	59	89.7
data	16-DPSK	7/8	276	139.8

Table 1: PACTOR-II speed and encoding levels with the resulting throughput rates
(all throughput rates are net rates referring to 8-bit ASCII)

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Part 2: Description of the PTC-II

I. Introduction

This second part of the PACTOR-II series explains the final version of the PTC-II hardware. As already indicated in the first part, the DPSK modulation system makes it mandatory to use a DSP as the interface to the short wave transceiver. Additionally, the convolutional coding with Viterbi decoder requires very high processing power, more than available in any existing modem on the Amateur Radio market.

However, the many wishes, ideas and suggestions from the ranks of the Radio Amateurs, have finally led to the development of an even more complex and flexible unit than necessary to implement the PACTOR-II system. For example, it has been the wish of many for a long time, to be able to operate not only with usual digital HF modes, but also to cover VHF and UHF Packet Radio at the same time, with one unit. Unlike currently available in existing units, a comfortable built-in mailbox should allow simultaneous access from all communications channels with the same priority, for example in Packet Radio on 23 cms with 9600 baud and on 70 cms with 1200 baud. Naturally, during this time no PACTOR or AMTOR connect on HF should be lost or ignored. This forces the use of a RISC (Reduced Instruction Set) processor for fast processing of the HDLC Packet protocols. As the majority of modern HF transceivers can be programmed via a serial interface, another wish that has slowly formed, is to use this feature for remote control of the transceiver. To set up a mailbox that scans various frequencies on HF, external computer and software is no longer required. Additionally, you could utilize your home based PTC-II whilst on the move, or from a remote location using Packet Radio. Instruct the HF transceiver to tune to a specific frequency, then to make a connect in PACTOR to a particular mailbox and read the messages.

These and many more ideas have led to hardware of very high performance. Due to the use of signal processing, the PTC-II is very flexible, and allows a great variety of different applications to be implemented. These range far wider than those written of up to now. Those technically talented users can make their own programs and modules, which may be loaded via the serial interface into the flash memory of the PTC-II. The possible uses are almost unlimited, as the PTC-II provides a complete, very high performance development platform for DSP and 68020 applications. From simple external control functions (e. g. automatically turning the antenna to the connecting station), or audio processing functions (e. g. super-steep sided FIR filters 400th order for CW, automatic N-times notch filters, etc.) right up to complex functions, like an audio spectrum analyser or extra operating modes, whether known or still to be invented, may be implemented.

The PTC-II has come on the market in March 1995. However, as some of the components used, among them the new DSP chip, are still difficult to get and due to the great demand for the unit, the time of delivery may still be up to 4 weeks. The price of the basic version of the PTC-II with 512k static RAM without PR-Modems is 950$ (USD) plus shipping (airmail outside Europe: 35$). VISA and Master cards are accepted.

II. The Processor Section

As has been made clear in the introduction, to achieve simultaneous processing of three communications channels along with the signal coding of PACTOR-II, a powerful computer is essential. A 32-bit processor system has been designed, based on the new communications processor 68360 (QUICC) from Motorola. This processor contains an expanded 32-bit version of the well known 68020 CPU, as used in many powerful computers, together with four separate programmable serial communications ports, the so-called SCC's, implemented as a RISC processor. Two of these SCC's serve as the interfaces to the Packet Radio modems. The third SCC is used as RS-232 interface to the terminal. A buffer chip MAX207A provides the correct RS-232 voltage levels. The baud rate to the terminal is detected automatically, but can also be determined by software command. The last remaining SCC serves as interface to the HF transceiver for remote control purposes. Four RAM chips with 8 bits each are required, to cover the 32 bit wide data bus. These can vary between 4 times 32k x 8 up to 4 times 512k x 8. The PTC-II can therefore have a maximum of 2 MB of static RAM, which plays a large part in running the mailbox and internal administration as well as external programs, that may be loaded into the PTC-II in addition to the operating software. In order to further expand the possible applications, the PTC-II may also contain additional dynamic RAM in the form of a 72 pin SIMM module of up to 32 MB. The operating system is to be found in a flash memory of up to 512k*8. Additionally, it is possible to load programs over the serial interface from the terminal, which would enable the PTC-II to do a totally different job, as already mentioned in the introduction. Operating parameters for the PTC-II that should be resistant even to a deep reset are also stored in the flash memory. Data in this kind of memory remains stored even when no voltage is applied, but contrary to an EPROM, it may be electrically erased and re-written whilst in circuit. That makes it very easy updating the system or running different programs on the PTC-II. A battery-backed-up real-time clock and other features of the previous PTC are of course still included.

III. The HF Modem with Signal-Processor

The 50 MHz version of the XC56156 DSP from Motorola forms the interface to the HF transceiver. As the clock frequency is programmable, it is automatically adjusted to suit the work of the moment. For easy tasks, such as FSK, the processing speed can be reduced, yielding a corresponding saving in energy. The DSP contains a built-in 16-bit digital to analog converter, with the help of which the audio output signal to the transceiver is generated, be it simple AFSK or the complex phase modulation of PACTOR-II. The output amplitude is also programmable and may be set in the range between 10 and 1000 mV by software command. The normally required 'Mic Gain' potentiometer is thus missing. It is also possible for the PTC-II to control the output power of the transceiver, so that the power to maintain the link may automatically be adjusted to an optimum value. No more power than needed being used, which not only saves on the electricity bills, but can considerably extend the life of transmitting components and additionally causes less interference to other stations.
For the signal input, the DSP uses a Sigma/Delta analog to digital converter with a 16-bit dynamic range (14 bit effective), which enables the normally necessary Anti-Aliasing filter to be dispensed with. With the exception of the decoupling OP-AMP at the input and output of the DSP, no further components in the signal path are required. The DSP contains some built-in static RAM, which in the PTC-II, is further expanded with 4 additional, very fast, static RAM's. The size of this RAM is 64k-words (16 bit) and is not variable. This enables difficult algorithms, for example 4096 point FFT, to be used. As the DSP has direct access to the main processor data bus, it does not tie up an SCC. The exact receive frequency of PACTOR-II is very quickly and reliably adjusted by software, using a newly-developed tracking method. In addition, the DSP is able, through pulsing the up/down function (which almost every modern transceiver has as microphone buttons) to automatically change the tuning for optimum results. The up/down keys are simulated by transistors, which pull the respective connection to ground.

IV. The PTC-II Power Supply

The PTC-II contains two power supply input options. Either it may be supplied via a special DC input connector, or directly from the HF transceiver via the connecting cable and socket. The two options are decoupled via diodes and feed a switching regulator. This has a high efficiency, and generates the 5V supply for the digital section. The supply voltage can vary between 8 and 20 volts. The current requirement, due to the use of the switching regulator, is dependant upon the supply voltage and the Packet Radio modems used. The higher the supply voltage, the lower the current consumption. This reverse proportionality is due to the fact that the power consumed is a product of voltage and current, and must be virtually the same before and after the regulator. The efficiency of the regulator is almost unaffected by the value of the supply voltage. The power supply input of the PTC-II contains special filtering, so that the switching harmonics from the regulator cannot reach the outside world. The operating voltage is internally fused with a 5x20 mm fuse. Of course an extra fuse is delivered with each unit to prevent problems in countries with different standards.

V. The Display and Indicator Unit

The display and indicator unit is built on a separate circuit board, and sits at right angles to the main board, connected by soldering pads. It carries a tuning indicator of 15 LED's, 15 further LED's to display the various operating parameters and a 10-character 5x5 dot matrix LED display. Most of the LED's, including the tuning indicator, are dual colour types, to increase the information densitiy and the ease of reading the display. The tuning indicator, for example, changes from red to green as soon as the tuning is optimum for the chosen operating mode. The 10-character LED display shows the operating mode and thus eases the display of any possible future update modes, as the PTC-II is more than sufficient for modes such as FAX, CLOVER-II, etc. Additionally, various status information as well as the call of connecting stations is also given on this display, thus in many cases there will be no need to switch on a terminal. The display is readable from a distance and from unsuitable viewing angles. The brightness is programmable and can be adjusted by a software command.

VI. The Packet Radio Modems

The ability to operate Packet Radio with the PTC-II is an integral part of the operating system, and therefore available on all units. The PTC-II is, however, mainly an HF controller, and thus the Packet Radio modems are implemented as modules, to be plugged in if the need arises. This enables a certain amount of mechanical compactness (the entire PTC-II is approximately the size of a modern VHF mobile transceiver). It also prevents those who only need an HF system from being forced to pay for an unwanted Packet Radio modem. The PTC-II contains connectors in the form of double PCB strip headers, on to which the modems can be easily plugged as required. There is space provided for two modems, which are automatically sensed when present. Two types of Packet Radio modems will be offered. A simple and cheaper version using the well-known modem chip TCM3105 for 1200/2400 baud, as well as a version with the XC56156 DSP chip. The DSP version is able to accomodate all baud rates from 300 to 9600 baud. The switching is accomplished by a software command. DSP programming and the clock are supplied from the main board, so that, apart from the DSP chip itself, virtually no extra components are required for the signal processing. Additionally, the DSP modem board has space for an EPROM and its own clock generator, as well as baud rate switching. These enable the modem board also to be used either as a stand-alone modem, or together with other equipment. It delivers the usual Packet Radio signals of RxD, RxClock, TxD, TxClock and DCD. It is thus compatible with all other Packet Radio systems. Even the connections to the double PCB strip header are compatible with the usual Packet Radio system standards.
The Packet Radio boards are not yet available however. They will come on the market later this year, together with the corresponding firmware upgrade for the PTC-II.

VII. The PTC-II Construction

The PTC-II is made up of two printed boards, a main board of 147x170 mm, and a front board which, as described above, contains the displays and is mounted at right angles to the main board. The main board is a 6-level multi-layer construction and contains internal ground and supply voltage areas. On the back is the DC input connector, an on/off switch, an 8 pin DIN connector for the HF transceiver, two 5 pin DIN connectors for Packet Radio, an 8 pin Mini-DIN socket for the transceiver control as well as a 9 pin SUB-D socket for the terminal connector. All DIN plugs are delivered together with the unit. Every single pin of every socket has its own filter in order to improve the HF rejection in strong RF fields, as well as to prevent unwanted radiation of electromagnetic energy. On the front is a row of 52 finger-pads for solder connection with the front board, a mounting method used on all SCS controllers. The construction is largely SMD. The flash memory and four static RAM's are socketed to enable easy system upgrades. The RS-232 interface chip is also in a socket to allow easy replacement in event of damage. The SIMM module, due to its construction, needs a holder without which it cannot be mounted. An 8 way DIL switch is also included so that various parameters may be set that should not be changed via software. The whole is enclosed in an aluminium profile case, well known from previous SCS-PTC's and many TNC's. Both front and rear of the case are silk-screen printed, at the front using three colours. The green and red lettering of the dual colour LED's explain their meaning when lighting green or red, respectively.
A block diagram of the PTC-II unit is shown in figure 1.

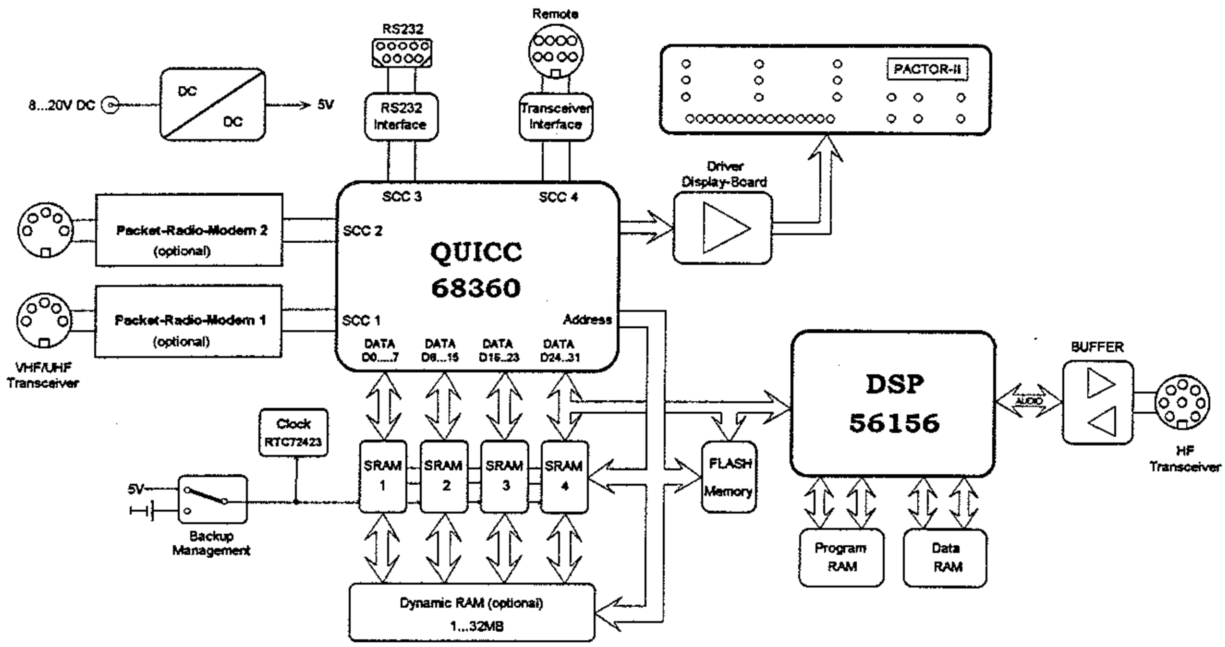

Figure 1: Block diagram of the PTC-II