

## **FFI RAPPORT**

### **NATO STANDARDS FOR HF COMMUNICATIONS - an overview and technical description**

JODALEN Vivianne, OTNES Roald, SOLBERG Bjørn

**FFI/RAPPORT-2004/02015**



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THESAURUS REFERENCE: 8) ABSTRACT During the 1990's many STANAG's (Standard Agreements) on HF communications were developed and agreed upon within NATO. The standards cover the lowest layers of the OSI model containing radio functionality, modem waveforms, datalink protocols and some networking aspects. Some of the standards are very complex. This report gives an overview of the technical functionality of the standards and summarizes their ratification and implementation status as of August 2006. The report also gives descriptions of the American military standards at HF which are closely related to the NATO standard. This report was originally published in 2003.				
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**CONTENTS**

	<b>Page</b>
1 INTRODUCTION	7
2 THE OSI MODEL FOR DATA COMMUNICATIONS	8
3 THE HF HOUSE OF STANDARDS	9
4 STANAG 4203	12
5 STANAG 4285	12
5.1 Technical description	13
6 MIL-STD 188-110	15
6.1 Mil-Std 188-110A	15
6.1.1 Technical description	15
6.2 Mil-Std 188-110B	16
7 STANAG 4415	17
7.1 Technical description	18
8 STANAG 4539	18
8.1 Technical description of the high data rate waveforms	19
9 STANAG 4197 AND ASSOCIATED SPEECH CODING TECHNOLOGY	21
10 STANAG 5066	21
10.1 Technical description	22
10.1.1 Subnetwork Interface Sublayer (SIS)	23
10.1.2 Channel Access Sublayer	24
10.1.3 Data Transfer Sublayer	24
10.1.4 Automatic change of data rate	25
10.1.5 Automatic frequency selection	25
10.1.6 IP over STANAG 5066	25
10.1.7 STANAG 5066 Edition 2	26
11 STANAG 4538	26
11.1 ARCS – Automatic Radio Control System (3G)	28
11.2 Technical description	28
11.2.1 Link set up	28
11.2.2 Data link protocol	29
11.2.3 Waveforms	30
11.2.4 Subnetwork Interface layer	31
11.2.5 Harris's implementation of STANAG 4538 and future developments	31

12	MIL-STD 188-141	32
12.1	Mil-Std 188-141A	33
12.1.1	ALE (2G)	33
12.1.2	Technical description	34
12.2	Mil-Std 188-141B	36
12.2.1	Appendix A: Automatic Link Establishment System	36
12.2.2	Appendix B: Linking Protection	37
12.2.3	Appendix C: Third generation automation of HF link	37
12.2.4	Appendix D: HF radio networking	37
12.2.5	Appendix E: Applications for HF radio networks	38
12.2.6	Appendix F: Techniques for anti-jamming and anti-interference	39
12.2.7	Appendix G: HF data link protocol	39
12.2.8	Appendix H: Management information base for automated HF radio networks	39
13	STANAG 4444	39
13.1	Technical description	40
13.1.1	Physical layer	42
13.1.2	Data link layer	43
13.1.3	Network layer	44
13.1.4	Channels and frequency management	45
13.1.5	Time-Of-Day management	45
13.1.6	Net services	45
13.1.7	Security	47
14	EW PROPERTIES OF THE HF WAVEFORMS	48
15	SUMMARY AND OUTLOOK	49
A.1	Glossary	52
	Bibliography	54



## **NATO STANDARDS FOR HF COMMUNICATIONS - an overview and technical description**

### **1 INTRODUCTION**

At the end of the 1980s, NATO initiated standardisation of military data communications in a number of frequency bands. During the 1990s a set of standards for HF communications were successfully produced, although the initial attempt at standardising the other frequency bands was not entirely successful. Attempts are now once again in progress to establish standards for VHF and UHF.

During the ten year period of HF standardisation the responsible working group has changed name and affiliation a couple of times. In recent years the group has been organized under the NATO Consultation, Command and Control Board (NC3B) of NATO and has been designated AC/322/SC6 BLOS COMMS AHWG/1, hereinafter referred to as the AHWG (Ad-Hoc Working Group on Beyond Line Of Sight Communications). From 2003, VLF is also a responsibility of the AHWG. The AHWG has received its assignments from, and has reported to, SC6 (CNSC).

The development of a NATO standard follows this route: The working group responsible for developing the standard agrees upon a technical solution through discussions and test results, avoiding conflicts and majority voting. NATO then sends the STANAG proposal out for ratification in the NATO countries. If a country ratifies a STANAG, it is obliged to implement it if the functionality that the standard provides, *is* going to be implemented. Reservation to certain parts of the STANAG can be made by the nations. If a certain number of ratifications are obtained, NATO decides to promulgate the STANAG. By promulgation a STANAG is official announced by the NSA (NATO Standardization Agency) to be the NATO recommended standard.

Although the standardisation of HF communications is effectively complete, the group continues to meet twice a year. It has become evident that proposals for changes in the standards, either of important technical character or of editorial nature, arise as suppliers implement the standards and operators gain user experience. The group “maintains” and updates the HF standards. Efforts are also in progress to update the VLF standard.

This report first provides an overview of all the standards which have been produced and then considers each individual standard. Each standard is described at an overall technical level, indicating relationships with other standards, including the American military standards. Finally we depict the ratification status of each standard. The report is primarily aimed at procurement agencies and HF communications planners with basic knowledge in communications engineering.

## 2 THE OSI MODEL FOR DATA COMMUNICATIONS

The ISO/OSI model for *data communications* divides the activities of a data network into seven separate functional layers. The model suggests that protocol standards can be developed within each layer, although the model itself does not provide any standards. Layer *n* of host machine A appears to communicate directly with layer *n* of host machine B, with the rules of this communication being provided by the protocol(s) at this layer. In reality, the data stream is transmitted vertically down through the underlying layers and up to layer *n* of the receiving machine, as shown in Figure 2.1. An advantage of this layered structure with different functionalities at each layer is that the technology and protocols for a single layer may be replaced without the need for changes in the rest of the system. All network nodes contain functions of the three lowest layers, while the upper layers cater for end-to-end functionality and are only found at nodes which need to exchange user traffic.

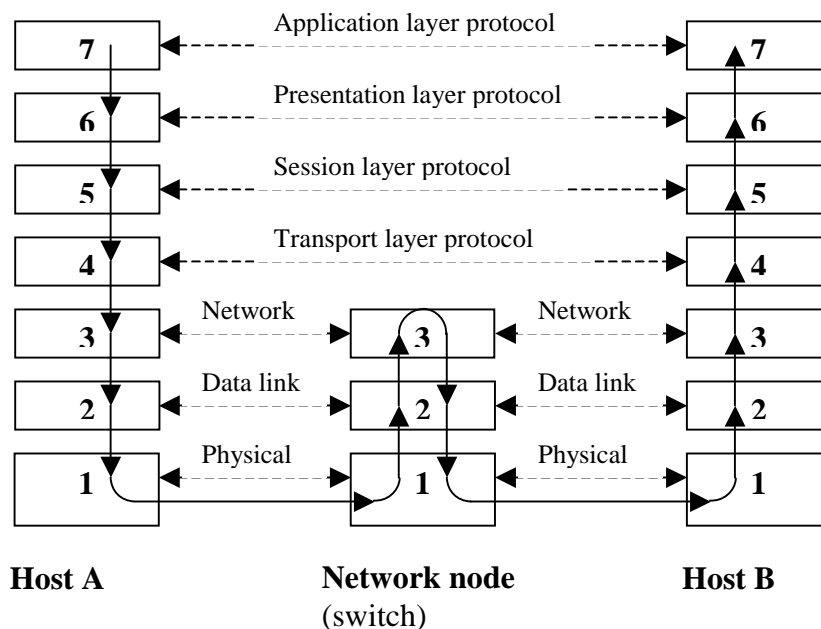


Figure 2.1 The ISO/OSI model for data communications

The OSI model is widely accepted and is referred to in many contexts, including the field of radio communications, although this latter field can call for additional functions which are not described in the original OSI model for data communications. The HF standards standardise protocols at the two lowest layers of the OSI model.

The architecture of the Internet is also a layered structure of network activities, and the OSI model can be applied to Internet communications. However, it is more common to use a four-layer model, as illustrated in Figure 2.2. One of the differences between the OSI model and the Internet architecture is that the latter does not have such strict and independent layering. Applications are free to connect to any underlying layer down to the networking layer (see

Figure 2.2). At the same time there is a very strong link between some of the layers, for example between the transport layer (TCP or UDP) and the IP layer.

In the following chapters, the HF standards for data communications are considered with reference to the OSI model.

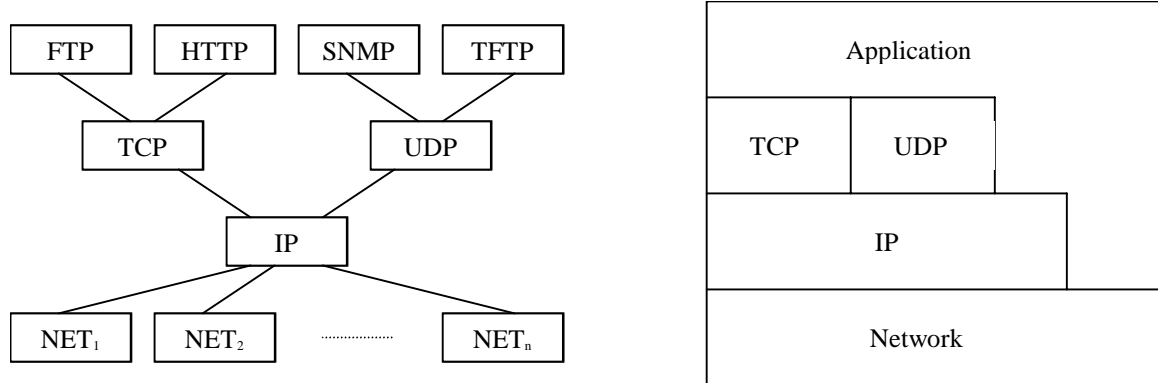
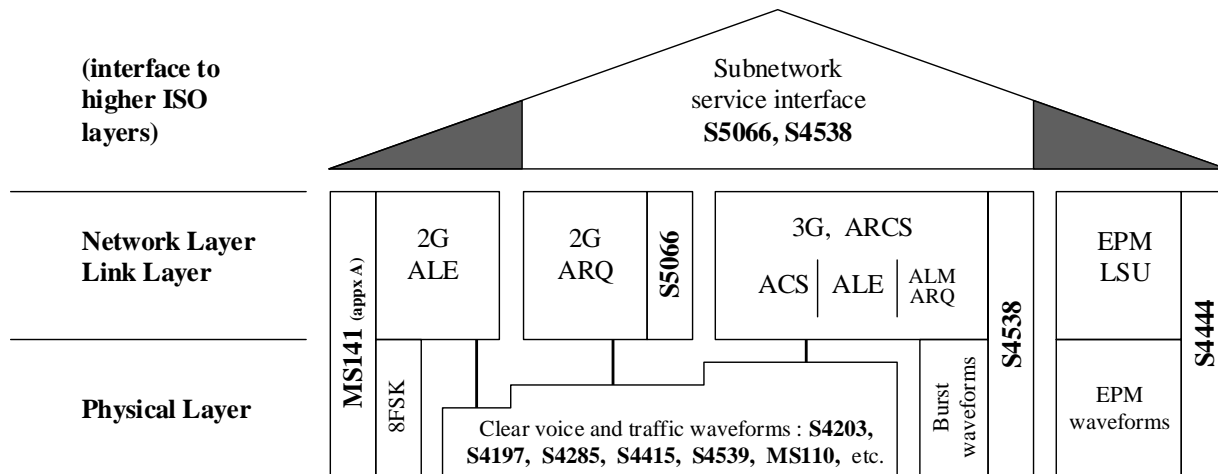


Figure 2.2 Internet protocols in various “layers”

### 3 THE HF HOUSE OF STANDARDS

Both the NATO standards and the American military standards (Mil-Std) for HF communications standardise protocols at the two lowest layers of the OSI model. The “HF House” illustrated in Figure 3.1 implies that the standards cover the *three* lowest layers, including the network layer, but this is not the case if the definitions of the OSI model for data communication are strictly followed. Hence the figure is somewhat misleading. (Mil-Std 188-141B contains traditional network functionality but is not included in NATO’s HF House.) The reason why the HF House diagram includes the network layer is probably a looser definition of which functions belong to the network layer and the fact that HF radio communications require other services which are not included in data communications, see for instance the description of STANAG 4444.

Each of the “rooms” in the HF House represents a single standard, except for the box at “Level 1” which contains several standards. The standards represented by boxes spanning both levels contain functions at both the physical and the data link layer. The lines between the boxes at “Level 2” and the box which only resides at “Level 1” indicate that data link functionality and physical functionality can be combined in the respective standards. In the roof of the house (the Subnetwork service interface), two standards are mentioned, STANAG 5066 and STANAG 4538, which define how external applications can connect to the underlying HF network. Since the specification of this does not belong to any of the OSI layers, these definitions are placed in a “roof” which points upward to higher levels.



**KEY** 2G: second generation 3G: third generation Smmn: STANAG MSmm: Mil-Std

Figure 3.1 NATO's "HF House"

The HF House contains the terms 2G and 3G, which refer to the second and third generations of *automatic HF radio systems*. These are systems that locate and select the best frequency automatically, consider the quality of the current link, and take action to improve the quality of the link if necessary. A distinct advantage with 3G systems is rapid and robust linking. The features of 2G and 3G technologies are expressed in table 3.1.

2G automatic HF	3G automatic HF
Modular, different functionalities may be located at different pieces of hardware	Integrated, all functionalities located in the radio
Asynchronous calling, no GPS time reference, gives longer call times	Synchronous calling, uses GPS time reference, gives short call times for members of the net
Linking using 8-FSK, not particularly robust at low SNR's	Linking using 8-PSK and Walsh-functions, very robust at low SNR's
Data rate adaptation based on an explicit change of waveform	Data rate adaptation based on adapting the code rate (code-combining)
Can utilize high data rate waveforms (up to 12800 bit/s) defined in STANAG 4539	Is limited to a maximum data rate of 4800 bit/s defined by the burst waveforms (*)
Offers a point-to-point service and a broadcast service for both packet and circuit switched data	Offers a point-to-point service for packet and circuit switched data and a point-to-multipoint service for circuit switched data only
Allows a more flexible frame size of forward transmissions, throughput efficient	Finite number of forward transmissions sizes, less throughput efficient (*)

Table 3.1 Comparison of 2G vs 3G automatic radio systems at HF. (\*) New technology (HDL+) is proposed for standardisation which will increase the maximum data rate and allow a more flexible transmission frame size

In a data network, the physical layer describe the physical cable connections and the electrical signals passing through these connections, for example the way in which 1 and 0 are represented, whether the signalling is duplex or simplex and how the signalling commences. In the case of radio communications, the protocols at the physical layer describe:

- The transmission format or frame structure (which bits represent preamble, data, known training bits or stop bits)
- Interleaving (how the bits are rearranged before transmission to combat fading on the channel)
- Modulation method and symbol rate
- Error correction coding

These properties constitute the concept of a waveform and are defined in modem standards. The HF House contains the modem standards STANAG 4285, US Mil-Std 188-110, STANAG 4415 and STANAG 4539.

The specifications of the actual radio equipment, for example frequency accuracy and stability, phase noise and gain control, are also located at the physical layer. These requirements are specified in STANAG 4203.

The data link layer divides the bit stream from the physical layer into frames of a certain size (which can be independent of the frame format defined at the physical level), uses a frame checking sequence to detect any bit errors and if necessary transmits an acknowledgement stating whether or not the frames were received with errors. Normally, an ARQ (Automatic Repeat reQuest) data link protocol will repeat the transmission until the frame has been received free of errors. At the data link layer the physical addresses to which the data frames are to be sent are also specified, as well as the way in which the physical link is to be accessed. In HF radio communication there is normally also a link set-up procedure before the traffic is transmitted and a link release following the completion of transmission.

Mil-Std 188-141A and STANAG 4538 define protocols both at the data link and the physical layer. The modem functions defined in these standards are closely connected with the link-layer protocols and provide optimal utilisation of these protocols. Nevertheless, the standards have a possibility of combining certain functions at the link layer with other modem standards, as shown in the diagram. Because STANAG 5066 contains protocols only at the data link level it has to be run together with a modem standard. STANAG 4444, which is an Electronic Protection Measures (EPM) standard, is run separately from other standards and defines protocols both at the physical and the data link levels.

We will now consider each individual standard in more detail, first the radio standard, then the modem standards and finally the data link standards and the EPM standard.

## 4 STANAG 4203

The title of STANAG 4203 is “Technical standards for single channel HF radio equipment”. The standard specifies properties of the radio which receives the audio signal (3 kHz bandwidth) from the modem and modulates it onto a carrier. It is located at the physical layer of the OSI model, but is *not* a modem standard, in contrast to the other standards which are located at layer one of the HF House. It is a tri-service standard.

Because a range of new modem standards were developed in the 1990s, it became necessary to produce a new version of STANAG 4203 which was better adapted to the new modem standards. Edition 3 was issued for ratification in 2002 and has now been ratified. Without Edition 3 of this standard the new waveforms will not perform optimally. Most major HF suppliers who have implemented the new waveforms and who also manufacture a radio product have implemented STANAG 4203 Edition 3.

Technical parameters specified in STANAG 4203 Edition 3 are:

- Radio frequency range
- Tuning
- Frequency accuracy and stability
- Frequency response and group delay time over a 3 kHz frequency band
- Phase noise
- Linearity
- Random emissions outside the frequency band and intermodulation products
- Operation mode (simplex/half-duplex)
- Switching time between transmitting and receiving
- Gain control
- Modulation of carrier wave

The last item specifies how different types of signals shall be modulated onto a carrier wave, for example that SSBSC (Single Side Band Suppressed Carrier) should be used for analogue and digital speech, teleprinting (RATT) and data transmission.

The standard also describes parameters for Independent Side Band (ISB) 6 kHz operation.

Two other standards which place stricter requirements than STANAG 4203 on the radio equipment are STANAG 4444 and STANAG 5511 (Tactical data Exchange – Link 11/Link 11B (Edition 4)).

## 5 STANAG 4285

The title of STANAG 4285 is “Characteristics of 1200/2400/3600 Bits Per Second Single Tone Modulators/Demodulators for HF Radio Links”. The standard is a modem standard specifying

protocols at the physical layer. It was promulgated by NATO in 1989 and is therefore quite an old standard. STANAG 4285 is a tri-service standard. The story behind it is that NATO realised that it needed an official NATO waveform, and a number of American and French engineers collaborated to produce it. The difference from Mil-Std 188-110A (which was produced at about the same time) is the result of compromises that were made between France and the US. NATO chose this waveform as its standard because it showed marginally better performance than Mil-Std 188-110A in over-the-air tests. In about 1993 NATO adopted STANAG 4285 for use in the broadcasting section of the BRASS (Broadcast And Ship-Shore) project. A large number of suppliers have implemented this standard in their modems, and a considerable number of S4285 modems are currently in use in NATO.

## 5.1 Technical description

As the title of the standard indicates, information is modulated onto a single tone or frequency; it is a serial tone waveform. A block diagram of the transmitter modem is illustrated in Figure 5.1.

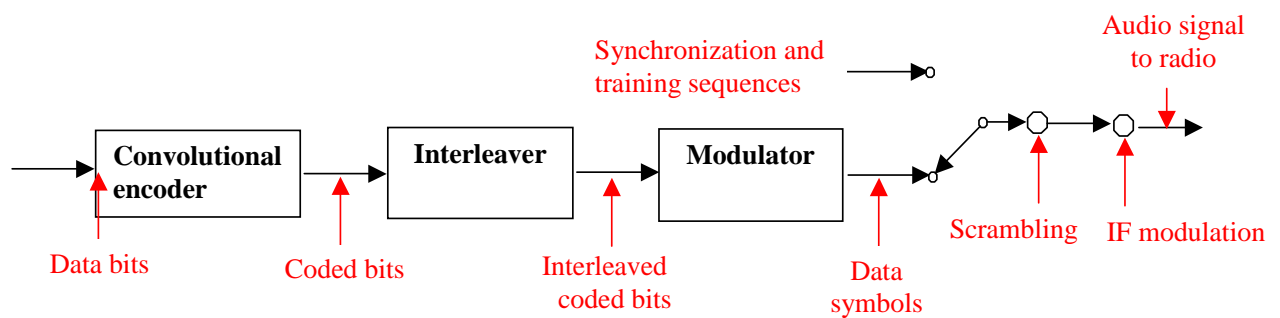


Figure 5.1 Block diagram of the transmitter modem of STANAG 4285 (and Mil-Std 188-110A). From [1].

The information data bits are first encoded using a convolutional code, generating a number of coded bits which is larger than the number of data bits. The convolutional code is most effective in additive white Gaussian noise (AWGN), but is not as efficient at handling noise bursts. The code rate  $R_c$  (ratio between number of data bits and coded bits) differs for the different information data rates, from 1 (uncoded) to 1/16.

After coding, the bit stream is interleaved using a convolutional interleaver. The interleaving rearranges the order of the bits so that a burst of noise does not damage a large number of subsequent bits, in which case the convolutional code performs poorly. The interleaving introduces latency in the receiver before decoding of the incoming bits, and STANAG 4285 provides a choice of two interleaver lengths, 0.853 s and 10.24 s. The greater the interleaver length, the better the bursts and fading are handled, but the greater the latency is in the receiver.

Following interleaving the bits are mapped to form modulation symbols, using 2, 4 or 8 PSK (that is 1, 2 or 3 code bits per symbol). These symbols are then multiplexed together with known symbols (training sequences) into a frame in which known synchronisation symbols occur first. The training sequences enable the receiver to be updated on channel conditions and to equalize inter-symbol interference caused by the channel. STANAG 4285 also re-inserts the synchronisation symbols at regular intervals (to maintain and if necessary recover synchronisation). The frame pattern efficiency  $R_f$  is only  $\frac{1}{2}$ ; in other words, half of the transmitted symbols represent data and the other half is synchronization and training. It should be noted that the synchronisation sequence in STANAG 4285 *does not* contain information about the data rate or the interleaver length in use. The receiver must therefore receive explicit information on what is being used. Consequently, STANAG 4285 does not have *auto baud* functionality.

STANAG 4285 can provide the following information data rates for different values of the code rate  $R_c$ , and of the number of bits per symbol  $Q$ : 75, 150, 300, 600, 1200, 2400 and 3600 bps. The relationship between the information data rate  $f_a$ ,  $R_c$ ,  $Q$  and frame pattern efficiency  $R_f$  is shown in Table 6.1.

The data and training symbols are then scrambled by multiplication with a random 8-PSK sequence so that the transmitted signal resembles an 8-PSK waveform, even when other modulation methods are being used.

The symbol rate (baud rate) is 2400 baud irrespective of information data rate, and this symbol rate requires a bandwidth of 3 kHz. The symbols are represented by phase and quadrature components modulated onto a 1800 Hz subcarrier frequency, and this 3 kHz signal centred on 1800 Hz (300-3300 Hz) is sent to the audio input of the radio. The radio then up-converts the signal to the carrier frequency by means of SSB modulation.

STANAG 4285 resembles Mil-Std 188-110A in many ways and gives almost the same data rates. The disadvantage of STANAG 4285 compared with Mil-Std 188-110A is that S4285 does not provide auto baud, and hence the throughput in the interaction with STANAG 5066 is degraded because explicit messages about data rate exchange must be transmitted.

The robustness against difficult channel conditions is different for waveforms providing different data rates. To achieve a bit error rate of less than  $10^{-3}$  at a data rate of 2400 bps with long interleaving typically requires a SNR of at least 12 dB, Doppler spread below 5 Hz and multipath spread below 6 ms. Waveforms with lower data rates have greater robustness and can handle poorer channel conditions.



## 6 MIL-STD 188-110

All the standards for military communications in the US are found in a series of Mil-Std 188 documents. A sub-series numbered Mil-Std 188-1xx covers systems which either use the analogue telephone network (long-haul) or systems which are of a tactical nature. This series of standards contains the American HF standards. These standards apply to all branches of the armed services. Mil-Std 188-110 is located at the physical layer of the OSI model and is a modem standard.

### 6.1 Mil-Std 188-110A

The title of this standard is “Interoperability and performance standards for data modems” and it was issued in 1991. Hence it is almost as old as STANAG 4285. In contrast with STANAG 4285, which is a pure modem standard for HF radio channels, 110A covers a broader spectrum of channel types. Many of the channels are typical analogue speech channels, for example the analogue wire line telephone network, and the standard determines how digital signals shall be adapted to existing analogue channels. Many of the *wire line* modulation methods prescribed for military systems are identical with civilian ITU standards. Some of the wire line modulation methods standardised in 110A seem to be somewhat outdated since quite different types of telephone networks exist today.

#### 6.1.1 Technical description

The main focus of 110A is on the waveforms (the modem) specified for HF radio communications, and it is probably these waveforms which most people associate with 110A. The serial tone waveforms specified in 110A are fairly similar to the waveforms in STANAG 4285 and consist of the same elements; coding, interleaving, modulation and frame structure. The following is a summary of the differences from STANAG 4285:

- 110A uses a block interleaver instead of a convolutional interleaver. This means that the rearrangement of bits is performed on a whole block of data at a time. Two interleaver lengths are available: 0.6 s and 4.8 s.
- The synchronisation sequence of 110A is much longer than that of S4285, at least 1440 symbols as compared with 80 symbols in S4285. 110A *does not* re-insert the synchronisation sequence; it is transmitted only once at the beginning of each transmission. This makes it difficult to restore lost synchronisation.
- The frame pattern efficiency (the proportion of the transmitted symbols which are known and therefore do not contain any information) is different for data rates above and below 1200 bps as shown in Table 6.1.
- Uncoded transmission gives an information data rate of 4800 bps for 110A and 3600 bps for S4285.
- The synchronisation sequence contains information about the data rate and interleaver settings, so that the receiver can adjust itself accordingly (auto baud).

Table 6.1 compares STANAG 4285 with Mil-Std 188-110A with regard to code rate, number of bits per symbol and frame pattern efficiency at different information data rates.

Data rate $f_a$ (bps)	110B			4285		
	$R_c$	$Q$	$R_f$	$R_c$	$Q$	$R_f$
(4800)	1	3	2/3			
(3600)				1	3	1/2
2400	1/2	3	2/3	2/3	3	1/2
1200	1/2	2	1/2	1/2	2	1/2
600	1/2	1	1/2	1/2	1	1/2
300	1/4	1	1/2	1/4	1	1/2
150	1/8	1	1/2	1/8	1	1/2
75	Robust			1/16	1	1/2

*Table 6.1 Parameter values for different information data rates in Mil-Std 188-110A and STANAG 4285.  $R_c$  = code rate,  $Q$  = number of bits per symbol and  $R_f$  = frame pattern efficiency. (110A is included in 110B, hence the heading “110B” in the table.) From [1]*

To achieve a bit error rate of less than  $10^{-3}$  at a data rate of 2400 bps with long interleaving typically requires a SNR of at least 15 dB, Doppler spread below 6 Hz and multipath spread below 6 ms, which is very close to the specifications of STANAG 4285. For 1200 bps the requirements for the same error rate are SNR > 10 dB, Doppler spread < 10 Hz and multipath spread < 7 ms.

110A also describes two options for parallel tone waveforms for use on HF channels; a 16-tone modem in Appendix A and a 39-tone modem in Appendix B.

There are many suppliers of this modem standard, which is in widespread use. It is especially attractive for use in conjunction with an ARQ scheme such as STANAG 5066, because it has auto baud facility. STANAG 4539 has adopted the waveforms of 110A for the 150 bps to 2400 bps data rates.

## 6.2 Mil-Std 188-110B

Mil-Std 188-110B was introduced in the year 2000 and is an updated version of Mil-Std 188-110A. New optional functionality has been added in new appendices. The most important difference between 110A and 110B is that the latter also specifies waveforms for high data rates, up to 9600 bps.

As for 110A, 110B is a modem standard also for other channels than HF. We cannot see any major changes in the description of these parts from 110A to 110B.

For HF, a new, optional, frequency hopping waveform has been added in 110B. Details are not described in 110B, but reference is made to Mil-Std 188-148 (Interoperability Standard for Anti-Jam (AJ) Communications in the High Frequency Band (2-30 MHz)). An optional robust waveform with an information data rate of 75 bps has also been added. This is identical with the STANAG 4415 waveform but does not have the same strict performance requirements. In addition to these two new waveforms, 110B contains the following new appendices:

- Appendix C (optional): Waveforms for data rates greater than 2400 bps. These waveforms are identical with the high data rate waveforms in STANAG 4539; see the description of this standard.
- Appendix D (optional): Subnetwork interface. This appendix describes how external applications can connect to the HF link or network. This is an expanded version of Annex A in STANAG 5066 entitled Subnetwork Interface Sublayer.
- Appendix E (optional): STANAG 5066 is recommended for use as a data link protocol.
- Appendix F (optional): A description of an HF waveform which combines non-contiguous frequency bands to achieve a higher data rate, for example 64 kbit/s by using four 3 kHz channels [6].

High data rate waveforms (Appendix C) have been implemented by several suppliers and are in operational use. Since these waveforms call for very good channel conditions their main use is in ground wave propagation over sea. However, ionospheric wave propagation of these waveforms will also be possible, as mentioned in the comments in Chapter 8. STANAG 5066 is now in common use in conjunction with the waveforms in 110B.

## **7 STANAG 4415**

The title of STANAG 4415 is “Characteristics of a robust, non-hopping, serial tone modulator/demodulator for severely degraded HF radio links”. The standard is a modem standard specifying protocols at the physical layer. It was promulgated by NATO in 1999. The standard is intended for tri-service use. Some implementations are known, but we do not know to what extent the standard is being used.

This standard was created on the basis of channel measurements made in the DAMSON project [2]. This propagation study showed that the channel conditions in northern latitudes can be extremely poor, with Doppler and multipath spread far in excess of that which has been classified as an “ITU-R Poor Channel”. In particular, Canada, the UK and Norway, countries operating far north, were interested in the development of a highly robust waveform.

## 7.1 Technical description

The information data rate is fixed at 75 bps, while the transmission symbol rate is 2400 baud, as for the other waveforms. Hence a large number of redundant bits are used in transmitting an information stream of 75 bps. Figure 7.1 shows a block diagram of the transmitter modem.

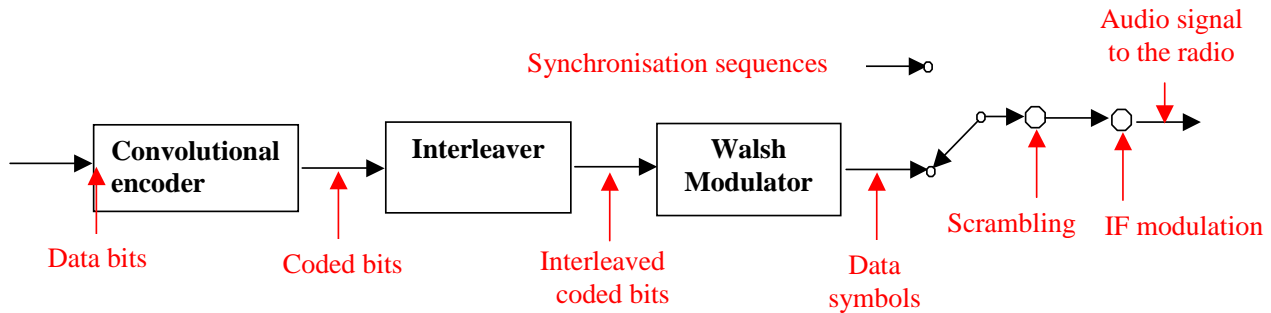


Figure 7.1 Block diagram of the transmitter modem of STANAG 4415

The convolutional encoder provides a code rate of  $R_c=1/2$ . In contrast with the waveforms in STANAG 4285, Mil-Std 188-110A and the high data rate waveforms in STANAG 4539, known training symbols are *not* transmitted, and the frame pattern efficiency is therefore  $R_f=1$ . The coded bits are however represented by orthogonal Walsh functions so that for each *pair* of coded bits, 32 BPSK channel symbols (one Walsh symbol) are transmitted. The total number of bits per symbol is therefore  $Q=2/32$ . Initially a synchronisation sequence is transmitted, containing information about the data rate and interleaver setting, so that the waveform has an auto baud facility in conjunction with an ARQ data link protocol.

The robust coding makes the standard a reliable communications carrier which works well with SNR values down to -7 dB, Doppler spread up to 40 Hz and multipath spread approaching 12 ms. The study in [3] showed that the accessibility of this modem waveform (assuming various frequencies can be used) lies between 90 and 100% irrespective of day/night/season on the measured paths in northern Scandinavia including Spitzbergen. The disadvantage is the low data rate (75 bps).

The waveform of STANAG 4415 is the same as the 75 bps waveform of Mil-Std 188-110B, but the requirements of receiver performance in STANAG 4415 are stricter than those of 110B.

## 8 STANAG 4539

The title of STANAG 4539 is “Technical standards for non-hopping HF communications waveforms”. The standard is a modem standard specifying protocols at the physical layer. It has been ratified by a sufficient number of nations and is in the process of being promulgated.

Several manufacturers supply the standard and it is in widespread use, particularly in naval networks in conjunction with STANAG 5066. The standard is intended for tri-service use.

Although the standard is relatively new, it does not only include new waveforms. It covers information data rates from 75 bps to 12800 bps by:

- Referring to STANAG 4415 for a robust 75 bps data rate
- Referring to Mil-Std 188-110 for 150-2400 bps data rates
- Defining new waveforms with data rates from 3200 bps to 12800 bps.

In all, these waveforms constitute a family of which all members provide auto baud characteristics, and which, in conjunction with an ARQ protocol (such as STANAG 5066), can give automatic adaptation of data rate to the channel conditions. For an HF system satisfying STANAG 4539, the abovementioned information data rates shall hence be supported in accordance with the abovementioned standards.

The low and medium data rate waveforms to which STANAG 4539 refer are described elsewhere in this report.

## **8.1 Technical description of the high data rate waveforms**

The high data rate waveforms defined in S4539 are identical with Appendix C of Mil-Std 188-110B. The performance requirements of implemented waveforms are however higher for STANAG 4539 than for 110B Appendix C; in other words, the two can communicate with each other, but a modem in compliance with 110B Appendix C does not necessarily exhibit as good communication performance as a S4539 modem.

The high data rate waveforms defined in STANAG 4539 consist in general of the same modules as illustrated in Figure 5.1 for STANAG 4285/Mil-Std 188-110A.

The error correcting code is a convolutional code with a code rate  $R_c=3/4$  for data rates from 3200 to 9600 bps. The code is therefore not as powerful as for the low rate and medium rate waveforms.

The interleaver is a block interleaver for which six different interleaver lengths can be selected: 0.12 s (Ultra Short), 0.36 s (Very Short), 1.08 s (Short), 2.16 s (Medium), 4.32 s (Large) and 8.64 s (Very Large).

The symbol rate, 2400 baud, is the same as for the lower data rates. When transmitting higher information data rates, higher order constellations are chosen; in other words, the number of bits per symbol,  $Q$ , can be 2, 3, 4, 5, or 6. PSK is used for  $Q=2$  or 3, and QAM is used when  $Q=4$ , 5 or 6. For higher order constellations, a high SNR is needed for correct demodulation.  $Q=6$  corresponds to a 64-QAM constellation.

The frame structure is more complex than that of the medium rate waveforms. The fraction of transmitted symbols containing information data (frame pattern efficiency) is greater ( $R_f=8/9$ ), which means that the channel estimate can be updated less frequently and the tolerance to Doppler spread is lower. STANAG 4539 also re-inserts the synchronisation sequence containing information about data rate and interleaving, making auto baud and re-synchronization possible.

The parameter values for the various information data rates are given in Table 8.1. The only parameter which varies with data rate is the constellation, with the exception of 12800 bps, for which an error correcting code is not used ( $R_c=1$ ).

Data rate $f_a$ (bps)	Code rate $R_c$	bits/symbol $Q$	Frame pattern eff. $R_f$
(12800)	1	6	8/9
9600	3/4	6	8/9
8000	3/4	5	8/9
6400	3/4	4	8/9
4800	3/4	3	8/9
3200	3/4	2	8/9

Table 8.1 Parameter values for different information data rates in STANAG 4539 and Mil-Std 188-110B Appendix C. From [1]

High data rate is achieved at the expense of robustness to low SNR and high Doppler and multipath spreads. Table 8.2 shows approximate values for the minimum SNR, maximum Doppler spread (DS) and multipath spread (MS) which STANAG 4539 tolerates at the different data rates. For lower interleaver lengths than those shown in the table, the performance is worse.

Information data rate (bps)	Interleaver (s)	Minimum SNR (dB)	Maximum DS (Hz)	Maximum MS (ms)
9600	8.64	25	2	4
8000	8.64	25	2.5	5
6400	8.64	20	3	5
4800	8.64	15	3.5	5
3200	8.64	15	4	6
2400	4.80	15	6	6
1200	4.80	10	10	7
300	4.80	5	20	7
75	4.80	-5	>20	>10

Table 8.2 Minimum SNR, maximum Doppler spread (DS) and maximum multipath spread (MS) for different information data rates in STANAG 4539 for  $BER > 10^{-3}$

With powerful transmitters ( $\geq 1\text{kW}$ ) and ground wave propagation over sea, high SNR with little distortion is obtainable. Under these conditions, the highest data rates in STANAG 4539 are achievable. In the case of ionospheric wave propagation and lower transmission power, SNR values above 20 dB do not occur very often, especially not at high latitudes. The availability of modems with different data rates over actual measured high latitude channels is described in [3]. On a short path (190 km) within northern Scandinavia with a large number of frequencies to choose among and 300 W transmission power, a waveform giving 2400 bps is available roughly 40% of the time averaged over the seasons and time of day. For a longer path from Spitzbergen to southern Norway (2020 km), the availability of the same waveform under the same conditions is on average roughly 80%. On the basis of this we can conclude that the high data rate waveforms are not suitable as *stable* communications carriers at northern latitudes. However, they can be useful to have available when the channel conditions permit, and when rapid, automatic adaptivity of the system is possible.

## **9 STANAG 4197 AND ASSOCIATED SPEECH CODING TECHNOLOGY**

The title of this standard is “Modulation and coding characteristics that must be common to assure interoperability of 2400 bps linear-predictive encoded digital speech transmitted over HF radio facilities”. This is an old standard which was first issued in 1984, with subsequent modifications. STANAG 4197 Edition 1 has been promulgated. The standard defines coding and modulation of a digital signal which is transmitted at HF, and in which the digital signal is a linear-predictive coded speech signal with a data rate of 2400 bps. The standard specifies that the speech signal shall first be coded with a Golay code and then 4-DPSK modulated within a 3 kHz frequency band. Parallel-tone modulation is selected with 16 tones for the synchronisation sequence and 39 tones for the data. The actual speech coding is specified in STANAG 4198 “Parameters and coding characteristics that must be common to assure interoperability of 2400 bps linear predictive encoded digital speech”. These two standards are old, and considerable developments have taken place since their introduction.

A new standard for speech coding has now been finalized, which in January 2006 was distributed for ratification. This standard, STANAG 4591, is based on MELP (Mixed Excitation Linear Predictive) speech coding and provides coded speech signals at 600, 1200 and 2400 bps. This standard can be used in conjunction with the modem standards in the HF House, such as STANAG 4285 and STANAG 4539, provided that these are run with zero interleaving. There exists also a low rate (800 bps) speech coder (STANAG 4479) which is intended for use in conjunction with for example STANAG 4444. STANAG 4479 Edition 1 has been promulgated.

## **10 STANAG 5066**

The title of this standard is “Profile for High Frequency (HF) Radio Data Communications”. Version 1.2 of this standard was distributed for ratification in 2000 and received sufficient

ratifications to be promulgated in 2004. The standard is intended for tri-service use, although it was originally developed for the ship-shore part of NATO's BRASS project which needed a link layer ARQ protocol. NC3A developed STANAG 5066 at the end of the 1990s, and is one of the few more recent standards which did not originate in the US/Canada. The standard can be run together with the modem standards STANAG 4285, Mil-Std 188-110A and B and STANAG 4539 (the last three have auto baud facilities). In the ship-shore part of BRASS, STANAG 4285 is currently used as the waveform in conjunction with STANAG 5066. However, there may be a move to STANAG 4539/Mil-Std 188-110B Annex F (allowing higher data rates) in the future.

Since the industry was quick to implement the new standard, there are 5-6 suppliers on the market. Rockwell-Collins, in particular, has cornered the market with its "HF Messenger" product, which has been purchased by the navies of several countries. However, the HF Messenger contains not just STANAG 5066, but also, among other things, Rockwell-Collins's proprietary e-mail application, Battleforce E-Mail. STANAG 5066 is a highly successful standard which has become widely used. Under the auspices of the HF Industry Association in the US, an Interoperability Conformance Meeting (ICM) is held a couple of times each year, at which industry and operational users discuss interoperability issues in connection with STANAG 5066.

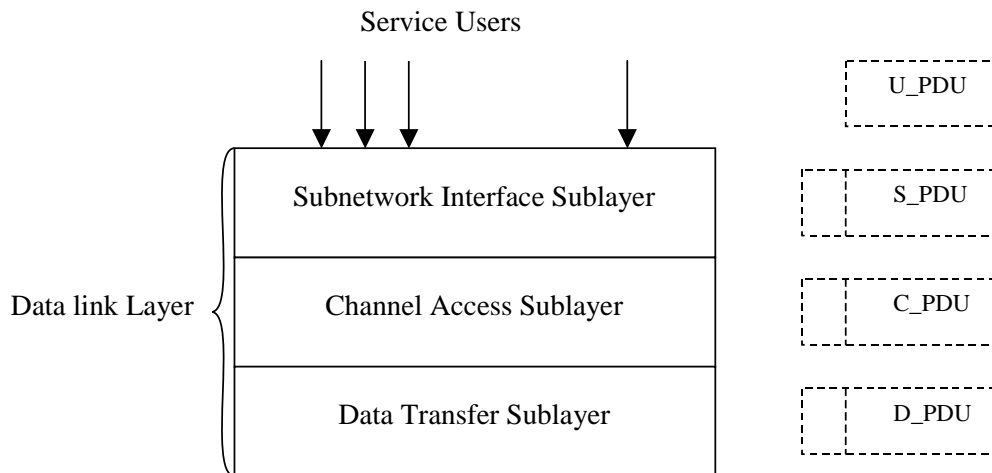
Based on several years' experience of the standard, a number of suggestions for changes and expansion have been put forward. The STANAG 5066 Version 1.2 is now referred to as Edition 1, and an amendment to Edition 1 has been approved by the AHWG and has been sent out for ratification (summer 2005). New functionality has been proposed for an Edition 2 of the STANAG which is now in preparation by NC3A and the AHWG.

## **10.1 Technical description**

STANAG 5066 is located at layer two (the data link layer) of the OSI model. It defines an interface to applications (clients) which will use the HF link or the HF network, and it defines an interface to the HF modem (the physical connection at HF). The standard was developed with the following single-tone waveform standards at layer one of the OSI model in mind: STANAG 4285, STANAG 4529 (1240 Hz Bandwidth HF Radio Link) and Mil-Std 188-110A. High data rate waveforms defined later which became STANAG 4539, can also be used with the S5066 data link protocol. Also, S5066 can be used in conjunction with parallel-tone modems, although this has not been tested to any extent.

Within the data link layer, the functions of STANAG 5066 have been divided into three levels or sublayers as sketched in Figure 10.1.





*Figure 10.1 A layered structure of functions within the data link layer defined in STANAG 5066*

The service users (such as e-mail, file transfer, IP) connect to a Service Access Point (SAP) shown by the arrows at the top of Figure 10.1. STANAG 5066 contains 16 SAPs, most of which are reserved for specific service users. For example, SAP 9 is dedicated to IP. A few SAPs are not defined, and are therefore available for future applications. The service users communicate with the S5066 data link layer by a set of service primitives, the formats and encoding of which are fully defined by the S5066. These service primitives contain the SAP ID's, the node addresses and the user datagram (U\_DPU) to be serviced by the S5066 protocol. The S5066 protocols will then service the U\_DPU and deliver it to the destination SAP of the destination node. Three protocol sublayers have been defined to provide the service, each sublayer exchanging x\_PDU's with its counterpart at the other node. S5066 defines these x\_PDU's and the procedures involved. Each sublayer communicates with its neighbouring sublayer by service primitives. However, these do not affect interoperability and is not subject to detailed specification by S5066.

### 10.1.1 Subnetwork Interface Sublayer (SIS)

The Subnetwork Interface Sublayer (SIS) defines the communication with the external clients which are to use the HF link or the network. If the clients have different ranks (degrees of importance), SIS can transmit higher priority traffic first. In addition, SIS establishes a connection with the destination node(s) and the connection can be one of three types:

1. Soft-link: There is no "handshaking" between the SIS at the transmitting and receiving nodes before data exchange commences. The Channel Access sublayer establishes a physical connection.
2. Hard-link: At the explicit request of the client, "handshaking" takes place between the SIS at the transmitting and receiving nodes before data exchange commences. The physical link which is established between the SIS at two nodes can be partly or

completely reserved for a single client at a node and prevent traffic to other nodes from being transmitted as long as the link is open.

3. Broadcast: The traffic comprises non-ARQ data to one or several destination nodes. Hence no physical link is established with any node.

Annex F in S5066 describes how certain “standard” applications can segment their data and code them into the primitives which are exchanged with the SIS of STANAG 5066. In the new version of STANAG 5066 (Edition 1, Amendment 1), the text in Annex F has been replaced in its entirety. Two client interfaces have been made mandatory; IP and the TCP/IP socket server. This means that a supplier of STANAG 5066 must have implemented the prescribed method of segmenting and coding, for example, IP traffic into the SIS primitives of STANAG 5066. The other client interfaces described in Annex F are optional; that means they have to be implemented only if the corresponding client type is implemented. Annex F of Edition 1 Amendment 1 also provides some enhancements to the IP client specification, for instance how IP version 6 can be supported.

### 10.1.2 Channel Access Sublayer

The Channel Access sublayer establishes and terminates the physical connection between two nodes. An external process (not defined in STANAG 5066) has decided the frequency at which the connection is to be established. There are no specified procedures within S5066 for testing whether the selected frequency is free, so collisions may occur. Depending on whether a hard-link or a soft-link connection is to be set up, an exclusive or non-exclusive physical link is established. Edition 1 Amendment 1 opens up the possibility for omitting the Channel Access Sublayer if it is assured that the two nodes are linked by some external process, for instance the Mil-Std 188 141A.

### 10.1.3 Data Transfer Sublayer

The most important functions of the Data Transfer sublayer are to segment incoming C\_PDUs from the Channel Access sublayer into smaller D\_PDUs and to transfer the actual user data to corresponding sublayers at the receiving node (via the modem and HF radios). STANAG 5066 can be run in two modes: ARQ mode and non-ARQ (broadcast) mode. The first mode can only be run in a point-to-point connection and the receiver transmits a selective ACK (acknowledgement) back to the transmitter when it has received a certain number of D\_PDUs. This provides a reliable service, with the transmitter being notified of the reception and trying to re-transmit until error-free reception has been achieved. The other mode is primarily used when a number of receivers are to be contacted simultaneously, but in this case the transmitter does not receive acknowledgment of the reception and the service is therefore unreliable.

In both the ARQ and Broadcast mode, there is an expedited delivery service in addition to the regular data service. Packets sent as expedited data are given priority over packets using the regular service.

There are several types of D\_PDUs which are transmitted between the Data Transfer layers; some contain only control information, some only user data and some contain both. Different D\_PDUs are used in different modes (ARQ, Broadcast). Broadcast operates in simplex mode, in other words the traffic flows only in one direction. ARQ can operate in half or full duplex mode. In full duplex, a D\_PDU contains user data from A to B and ACK for user data sent from B to A. The payload in D\_PDUs has a maximum size of 1023 bytes, but this can be determined by the user, and studies have shown that a size of around 200 bytes is optimum when the data rate varies. The number of D\_PDUs sent in one forward transmission is determined by the size of the flow control window at the Data Transfer Sublayer.

#### 10.1.4 Automatic change of data rate

The receiver recognises the need for a change of data rate and initiates it. The receiver indicates that a change of data rate is necessary in the control information part of the D\_PDU which is returned to the transmitter. The transmitter can then immediately change to a new data rate if waveforms with self-identification (STANAG 4539 or Mil-Std 188-110) are in use. If waveforms without self-identification (STANAG 4285) are being used, some D\_PDUs must flow back and forth to negotiate a new data rate before the change of data rate is effected. A condition for achieving adaptive data rate is that the modem in use has a remote control capability. In S5066 Edition 1 Amendment 1 the data rate change specification of the high data rate waveforms in S4539 has been expanded to allow a wider range of waveform types, including multiple channel modems.

#### 10.1.5 Automatic frequency selection

In contrast to STANAG 4538, STANAG 5066 is a pure data link standard and does *not* define ALE (Automatic Link Establishment). Either, a fixed frequency must be agreed upon, or it is possible to run STANAG 5066 in conjunction with an external ALE system, for example Mil-Std 188-141A. It shall also be possible to run third generation link set up (FLSU/RLSU) defined in STANAG 4538 in conjunction with the data link protocol in STANAG 5066. Former Marconi, now Selex Communications has implemented this for the Swedish Armed Forces.

In STANAG 5066 there are also procedures for ALM/frequency changing, but these are not mandatory in the standard.

#### 10.1.6 IP over STANAG 5066

Although STANAG 5066 can transmit IP traffic, the standard does not define a direct IP interface. For a S5066 network to serve IP packets, these need to arrive at the Subnetwork Interface Sublayer of S5066 as part of a service primitive. A S5066 IP client is responsible for the conversion between IP packets and the standardized SIS primitives, acting as a gateway between an IP network and the S5066 radio network. This represents a difference from the IP interface which Harris has implemented in their STANAG 4538 radio product.

### 10.1.7 STANAG 5066 Edition 2

A new edition of STANAG 5066 is now (fall 2006) in preparation by NC3A and the AHWG. Edition 2 aims at supporting IP based HF wide area networking as described in [4]. Edition 2 will include a set of new annexes; J to O. The main new functionality in Edition 2 concerns media access control (MAC) to allow multiple nodes in a small network (up to 8 nodes) to share a single frequency. One new annex describes random access control protocols and another annex describes a wireless token ring protocol. Still another annex is reserved for a future definition of TDMA. The MAC functionality has been included in the layered structure of STANAG 5066 in Figure 10.2.

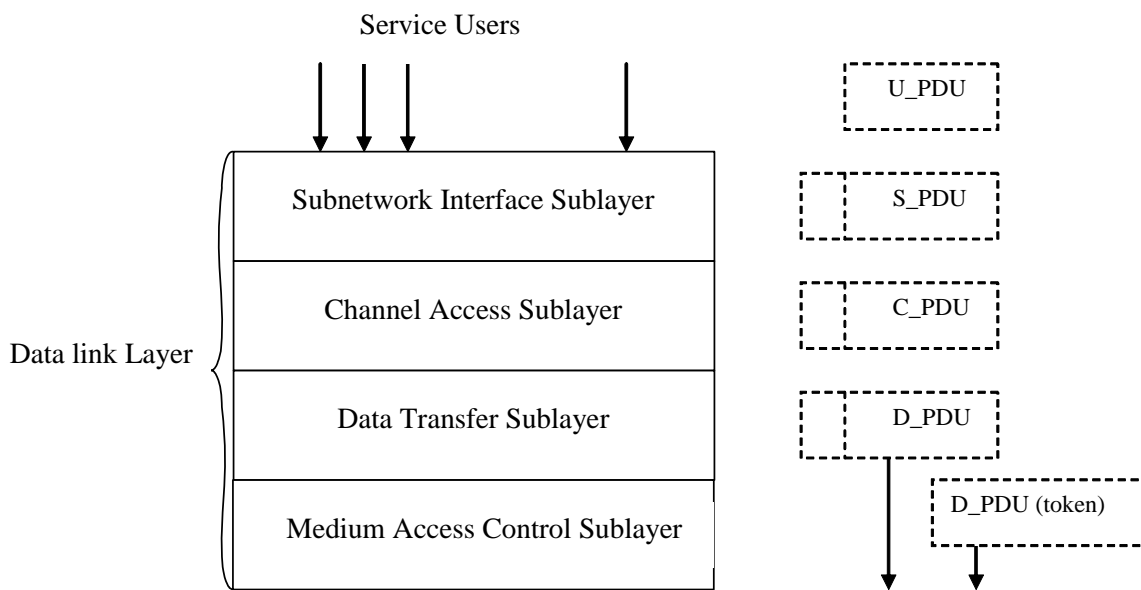


Figure 10.2 Protocol stack of STANAG 5066 Edition 2; MAC layer added.

Other new functionalities supported by Edition 2 are multiple, concurrent ARQ connections (soft links) with other nodes and a standardized address allocation plan.

A development principle for Edition 2 has been capability discovery between nodes and devolution to lowest common denominator. Data is exchanged at the most capable mode held in common. Management D\_PDUs for the wireless token ring protocol in Annex L are based on the existing D\_PDU message elements to support token management. The random access techniques standardized in Edition 2 Annex K have been chosen to meet common vendor practice and assure backwards compatibility with Edition 1.

## 11 STANAG 4538

The title of this standard is “Technical standards for an automatic radio control system (ARCS) for HF communication links (Edition 1)”. It was distributed for ratification in 2000 and it has been promulgated based on a sufficient number of ratifications. Also the Edition 1, Amendment

1 which contains technical clarifications and minor editorial changes has been promulgated without going through a new ratification process.

When NATO decided to develop a standard for automatic radio control, the American Mil-Std 188-141A, now referred to as the second generation of automatic radio systems, already existed. NATO was of the opinion that better solutions than 141A were achievable and decided to widen the concept to “ARCS” (Automatic Radio Control System). The ARCS concept initially consisted of three functions: ACS (Automatic Channel Selection), ALE (Automatic Link Establishment) and ALM (Automatic Link Maintenance). Significant overlap was found with third generation (3G) automatic radio system technology developed in the US with Mil-Std 188-141B. The US offered to adapt their 3G standard to meet NATO needs; this became Robust Link Setup (RLSU) in STANAG 4538. An alternative non-interoperable 3G mode, called Fast Link Setup (FLSU), was developed by engineers in the US, France and Germany. FLSU offers slightly faster link setup in small, lightly-loaded networks and was also included in STANAG 4538. These new protocols were evaluated against existing second generation (2G) technology, and were found to be superior in SNR performance. Backward interoperability with 2G ALE is mandatory for both 3G modes.

In the course of the standardisation process ACS was determined not to be a subject of standardisation. It is up to the vendor to implement frequency selection based upon the information which might be available, for example predictions, sounding or passive channel monitoring. The receiving HF station does not need to know anything about the frequency selection process, only the frequency that was selected. ALE and ALM are the functions which *have been* standardised in the current edition of STANAG 4538.

STANAG 4538 is identical with Mil-Std 188-141B, Appendix C, except that Mil-Std 188-141B excludes FLSU.

Harris Corporation was deeply involved in the development of this STANAG and they have been the leading vendor on the market for several years with their tactical radio implementation. Until 2004, there was no other STANAG 4538 product. However, in 2004, Telefunken Racoms completed their implementation of STANAG 4538 in a strategic HF system for the German Navy. This implementation includes Robust Link Setup (which Harris has not implemented). Former Marconi, now Selex Communications has implemented Fast Link Set Up from STANAG 4538 together with the data link protocol STANAG 5066 for the Swedish armed forces.

Some performance aspects of STANAG 4538 such as for instance link setup, is clearly better than those of second generation ARCS systems. There are reasons to believe that this 3G system will be preferred in many new HF procurements in the future, but it is also foreseen that 2G and 3G systems will continue to coexist. As an example, the British Army has a contract with Harris for the delivery of 10 000 radios, all STANAG 4538 capable, to the project Bowman.

## 11.1 ARCS – Automatic Radio Control System (3G)

STANAG 4538 is defined as the third generation of automatic HF systems. The term “third generation” implies:

- All HF stations in the network are equipped with accurate clocks and perform synchronous scanning of a set of pre-assigned frequencies. All stations change frequency simultaneously, and the current dwell channel of every station is always known, enabling very rapid linking.
- A highly efficient Automatic Repeat reQuest data link protocol is combined with several robust burst waveforms which are optimised for the data link protocol. The robustness of the communication adapts itself to the channel conditions by means of *code combining*.

These two properties of 3G technology roughly represent ALE and ALM, but in addition STANAG 4538 defines other ALM functions which are less well known.

It has been claimed that 2G is suitable for long distance naval and air force applications and that 3G is most suited to tactical communications systems. However, we cannot see that there is any convincing technical basis for this statement. This perception is probably based upon the fact that STANAG 5066 (2G) was primarily developed for ship-shore communications utilizing existing modems, the weight and dimensions of the equipment being of less importance. A data link protocol was therefore developed which was run on a separate PC and controlled the modem. The development of STANAG 4538 has been pushed ahead by the US, with Harris, being a manufacturer of *tactical* radios, in the forefront. Since Harris was quick to implement STANAG 4538 in a tactical manpack radio in which radio functions, modem, encryption, data link protocol and link set up are integrated in a single unit, STANAG 4538 has subsequently been associated with this integrated tactical radio product.

## 11.2 Technical description

The following is a slightly more technical description of STANAG 4538: The standard is located at the two lowest layers of the OSI model. The data link protocol at layer two is closely connected with the burst waveforms defined in the standard, and cannot be run with other waveforms. On the other hand, the link set up, which is also located at layer two, can be run in conjunction with other data link protocols, for example STANAG 5066, and with waveforms at “Level 1” of the HF House. In this case, STANAG 4538 establishes a line-switched connection which STANAG 5066 or the waveforms make use of.

### 11.2.1 Link set up

Two different protocols are prescribed for link set up in STANAG 4538; FLSU (Fast Link Set Up) and RLSU (Robust Link Set Up). RLSU is developed for congested channel conditions and/or a large network with heavy loading. RLSU uses separate call and traffic frequencies, which means that in the link set up phase the two stations agree on which traffic channel they will use and then immediately release the call frequency when traffic commences on the traffic channel. RLSU uses 5.4 second dwell periods, with multiple calling slots (selected randomly) provided to reduce collisions on calling channels. To further reduce calling channel congestion, station dwell patterns may be distributed over the calling channels.

Compared with RLSU, FLSU is a faster-scanning link set up protocol and is intended for use under less problematic conditions. In the opinion of some people it is adequate for most conditions. The core of both FLSU and RLSU is, as mentioned, that all members of the HF network synchronously scan a set of pre-defined frequencies using an accurate time reference. A FLSU station that wants to contact another decides which frequency it will use, jumps to that frequency immediately before the other HF stations arrive at it to check that it is free, and transmits a signal as soon as the other stations have arrived at that frequency. The dwell time at each frequency is 1.35 seconds, with binary exponential backoff used after calling channel collisions to reduce the probability of additional collisions.

Some of the possibilities available in connection with link set up are:

- Point-to-point for packet data transmission (two-way handshake)
- Point-to-point for line-switched data transmission (the waveforms in the central box at “Level 1” of the HF House), (also a two-way handshake)
- Point-to-multipoint for line-switched data transmission (one-way)
- An unsynchronised station (without GPS time) can call up a synchronised station (two-way handshake with an initial scanning call as in 2G)
- An unsynchronised station can call up and become synchronised with a station or network which is synchronised (also two-way with scanning call)

Sounding is a unidirectional transmission sent by a station to enable other stations to measure channel characteristics. This is often unnecessary in 3G systems due to the synchronous scanning, but the protocol and packet format are defined in STANAG 4538 for use when Link Quality Assessment (LQA) would be useful.

ALE protocols are also prescribed, for example how to return to link setup and switch to another frequency.

In scan mode, stations shall also be able to detect 2G calls from Mil-Std 188-141A and respond to these.

### 11.2.2 Data link protocol

The STANAG 4538 data link protocol is an ARQ protocol which can only be run in a point-to-point data packet connection. The data link protocol is designated xDL and is actually a family of protocols which can be grouped as HDL (High throughput Data Link) and LDL (Low latency Data Link) protocols. HDL is most efficient when large volumes of data are to be transmitted and the channel conditions are moderately good. LDL works best when transmitting small data volumes (irrespective of channel conditions) and when the channel is of poor quality (irrespective of data volume). However, in the latter case, it will take a long time for LDL to transmit a large data volume.

HDL and LDL protocols can be designated by a number, as in HDL3 or LDL512. The link protocol divides up the data volume to be transmitted into blocks of a given size. The number in the designation of HDL protocols signifies the number of 233-byte blocks (called packets) which are transmitted in one forward frame. For example, HDL3 transmits  $3 \times 233$  bytes in a forward frame. The receiver then returns an acknowledge signal (ACK) for the receipt of this frame and indicates if necessary which of the packets in the frame contained errors (selective acknowledgement). The transmitter will then retransmit these packets in the next forward frame. The number at the end of the designation for LDL protocols signifies the number of bytes which are transmitted as a single packet in one forward transmission. The acknowledgement signal states whether or not the entire transmission was successful; in other words, no selective ACK is provided. The size of the forward transmission can vary from 32 bytes (LDL32) to 5592 bytes (HDL24).

“Throughput” is a measure of how efficiently the data link protocol, in combination with the waveforms, transmits data. The throughput falls if the channel conditions make it necessary to retransmit packets many times. The maximum throughput of a link protocol is achieved when transmitting a large data file by the largest frame through an error-free channel; the time spent for establishing and releasing the link is then minimal in comparison with the time taken to transmit traffic, and there are no retransmissions. For HDL24, the maximum throughput is approximately 3200 bits/s and for LDL512 it is approximately 500 bits/s.

xDL is a code-combining ARQ protocol. This means that the initial transmission of a packet is transmitted uncoded (in the case of HDL). If the packet is received with errors, a coded version of the packet is transmitted next time. This can be repeated several times until finally the receiver has a number of “versions” of the packet. The different versions can then be combined to derive the actual data, thereby increasing the probability of correct decoding.

An additional datalink protocol called HDL+ has been developed and proposed for standardization by Harris Corporation. It is briefly described in section 11.2.5.

### 11.2.3 Waveforms

The difference in robustness between HDL and LDL is the result of the different waveforms which are used. The data link protocol is closely associated with the burst waveforms defined in the standard and which are located at layer one of the OSI model. Six burst waveforms (BW) are defined which are used in different contexts:

- BW0 for Robust Link Set Up
- BW1 for management traffic and HDL ACK
- BW2 for HDL traffic
- BW3 for LDL traffic
- BW4 for LDL ACK
- BW5 for Fast Link Set Up



All have different technical characteristics in terms of code rate, interleaving, frame format and synchronisation, and this gives them varying degrees of robustness. The most robust waveforms are used for the ACK signals, as it is important for the protocol efficiency that these are received correctly. The waveforms for link set up are also more robust than the traffic waveforms, hence even if a link is established it may still be impossible to transmit traffic. Typically, HDL (BW2) must have positive SNR values to work, while LDL (BW3) can handle SNRs down to -5 dB. The duration of a burst varies for the different waveforms, for example, an ACK for LDL takes about 0.5 seconds, while an HDL24 traffic frame takes about 10 seconds to transmit.

Associated with the new HDL+ data link protocol, two new waveforms have been proposed, see section 11.2.5.

#### 11.2.4 Subnetwork Interface layer

STANAG 4538 is also mentioned in the “roof” of the HF House under the heading “Subnetwork service interface”. This part of the STANAG should define *how* external applications, such as e-mail or an IP client shall connect to the HF Subnetwork. In the current version of STANAG 4538, an IP packet interface, an analog interface, a data terminal interface and a control interface are mentioned without further guidelines. For the next Edition of the STANAG the intention is to define a common subnetwork interface to both STANAG 5066 and STANAG 4538. STANAG 5067 may be a candidate for this.

#### 11.2.5 Harris’s implementation of STANAG 4538 and future developments

Finally, we have some comments on Harris’ implementation of STANAG 4538 in the Falcon II radio RF-5800H since this product has been on the market for many years now. Harris has so far implemented FLSU but not RLSU, and it seems unlikely that they will implement the latter. The radio chooses the data link protocol xDL automatically, based on earlier knowledge of the channel quality and the volume of data to be transmitted. The Harris radio has a direct IP interface, which means that the radio is capable of reading IP addresses and route IP packets. This is an efficient but not a standardized solution. However, the current version of the standard does not contain a specification for the subnetwork interface, and this is a highly desired specification in a new edition of the STANAG.

The Harris radio selects a frequency on the basis of a number of factors, among them acquired experience from earlier xDL communication, the point of time in the scanning cycle and explicit sounding that updates channel scores in the radio. These are Harris’s own algorithms for ACS, which have not been standardised and do not need to be. The use of sounding, which exchanges signals with another radio over-the-air, will represent a problem of interoperability with other radio suppliers. There is a suggestion to standardise sounding in a new edition of S4538, which appears to be very sensible based on our experience with the Harris type of sounding.

STANAG 4538 is a rather complex standard. During the implementation and early phases of testing, Harris found shortcomings of the standard and consequently deviated slightly from it. As long as there was only one product on the market, this was not a problem. Today, with more

vendors having a STANAG 4538 product, it is not given that the products from different vendors are interoperable. Most of the shortcomings of the original version of STANAG 4538 have been fixed in Edition 1 Amendment 1. There are further comments on interoperability in section 15.

3G technology at HF is not superior to 2G technology in all aspects. The 3G technology described in STANAG 4538 Edition 1 has a fundamental limitation by the maximum gross data rate of the HDL waveform of 4800 bit/s which is far below what is achievable with STANAG 5066 used together with STANAG 4539. Therefore Harris has developed a new data link protocol, HDL+, which combines the high data rate waveforms of STANAG 4539 with some of the features of the data link protocol in STANAG 4538. The same link setup procedure is used for HDL+ as for HDL/LDL. Some of the differences between HDL+ and the standardized HDL/LDL protocol are:

The 2-way traffic management handshake has been removed. Instead, a control burst segment using a new robust waveform has been introduced to each forward transmission. The control burst segment contains for instance the source address, the signal constellation of the adjoining high data rate message payload, a signal-to-noise estimate at the transmitter and a packet status field that identifies which packets are being sent. The data payload of the transmission uses another new waveform. As opposed to HDL/LDL, the HDL+ protocol is not synchronous and can have variable length forward transmission times. The ACKnowledgement message uses the same robust waveform as the forward direction control burst segment. It contains the source address, information about SNR, fade rate and multipath spread and a bit field that identifies which of the packets was received correctly. By using this information, HDL+ may adaptively modify the coding and signal constellation for each forward transmission to track the variations of the HF channel.

For very good channel conditions ( $\text{SNR} > 25\text{dB}$ ) HDL+ may give a throughput up to 10 kbps in a 3 kHz channel. For SNRs below 10 dB, the HDL/LDL protocols perform better than HDL+. This data link protocol has been implemented (and patented) by Harris, and it has been proposed for standardization within NATO. If the AHWG decides to standardize it, it will be a basic new functionality of a new Edition 2 of the STANAG 4538. This new edition will require a new ratification process.

A standardized multicast packet protocol is also desired for a new Edition of the STANAG.

## **12 MIL-STD 188-141**

The same comments which were made in introducing Mil-Std 188-110 also apply to Mil-Std 188-141, with the exception that Mil-Std 188-141 is a standard which covers the *three lowest* layers of the OSI model, the physical layer, the data link layer, and the network layer (though the last applies only to 141B). In the US Mil-Std system, only the most recent version can be

used for procurements, but for historical interest both the previous (141A) and the current (141B) versions are described here.

## 12.1 Mil-Std 188-141A

The title of this obsolete standard is “Interoperability and performance standards for medium and high frequency radio systems”. Hence, it is specific for HF and MF (down to 1.5 MHz) *radio systems* and does not apply to data modems in general, as Mil-Std 188-110 does. The first version was released in 1988, and two revised editions were released in 1992 and 1993.

The main part of 141A describes radio functions such as frequency accuracy, phase noise etc, in the same way as they are described in STANAG 4203 (layer one of the OSI model). If interoperability with other NATO countries is required, the current version of STANAG 4203 is referred to.

As regards modem functions for *transmitting traffic*, the standard refers to the current version of Mil-Std 188-110, or to the appropriate NATO standards if interoperability with other NATO countries is required. Modem functions which are needed to send ALE words to set up connections are defined by the standard itself in Appendix A, hence covering functions also at the physical layer (but not for the transmission of actual traffic). As far as we can see, the standard contains no references to data link protocols for *transmitting traffic*, but it defines the actual data link (ALE) protocol which *sets up a link*. (However, in 141B, a data link protocol for the transmission of traffic is referred to.)

For more secure communications, the standard refers to an anti-jam mode defined in Mil-Std 188-148 (Interoperability Standard for Anti-Jam (AJ) Communications in the High Frequency Band (2-30 MHz)).

### 12.1.1 ALE (2G)

Mil-Std 188-141A is normally associated with the automatic, adaptive functions defined in Appendix A. When the term “ALE” is used, the system described in this Appendix is referred to.

By an automatic, adaptive system is meant that the system itself monitors the quality of the transmissions and adjusts certain parameters to achieve optimum performance at all times. This includes functions such as:

- Scanning a set of frequencies to detect calls
- Link establishment (ALE) at a selected frequency
- Sounding: A specific signal is transmitted which is monitored by listening stations to achieve knowledge about channel conditions on the actual channel

- Link Quality Analysis (LQA): Based upon soundings and earlier communication, the individual station performs a quality analysis of the channels, in order to assist the ALE in selecting an operating frequency

All these functions support the transmission of traffic. When a link is established, an external process (or user) is notified, and the communication switches to a voice or data transmission phase.

The 141A functions are either located in a separate ALE controller connected to the audio and control inputs of the radio, or they may exist as software within the radio.

In the HF House, 141A embraces the physical layer and the data link layer. According to the standard itself, the whole standard belongs to the data link layer, which is somewhat misleading in view of the general understanding of which functions belong to which layers. However, it may be justifiable since the physical functions are so closely associated with the data link protocol itself that it would be difficult to replace the physical functions with other functions. (This applies also to STANAG 4538, although there the physical functions are not defined as belonging to the data link layer.)

#### 12.1.2 Technical description

ALE in 141A is based on the exchange of 24 bit ALE words. The first three bits in the word define which of eight possible ALE words is currently being transmitted. The following eight words can be transmitted:

THRU - 001  
 TO - 010  
 CMD - 110  
 FROM - 100  
 TIS - 101 (THIS IS)  
 TWAS - 011 (THIS WAS)  
 DATA - 000  
 REP - 111 (REPEAT)

The remaining 21 data bits in each word are often divided up into 7 bit characters. If, for example, the word TO is transmitted, this command is a call to one individual station or a network call to many stations. The data field of the ALE word contains the first three characters of the destination address. If the address is longer than three characters, the rest of the address can be transmitted with the subsequent DATA and REP words, up to a maximum of five words, which can therefore contain an address of up to 15 characters. The sequence of ALE words which is transmitted is then: TO, DATA, REP, DATA, REP. If a call is being made to many stations, there is a pre-programmed network address which shall be transmitted.

We will not explain all the ALE words, but merely point out that the CMD word combined with DATA and REP can be used to transmit (orderwire) control information such as:

- LQA data
- Frequencies (optional, and rarely implemented)
- Which modem is to be used (optional, and rarely implemented)
- Which encryption is to be used (optional, and rarely implemented)
- AMD - Automatic Message Display. (This is a method of sending short text messages in the ALE transmission itself without handing over control to a traffic modem. It is mandatory for all implementations.)

The standard divides up the data link layer into three sub-layers: The FEC sub-layer, the linking protection sub-layer and the ALE sub-layer. The FEC layer defines modulation and coding, the linking protection layer provides security mechanisms against intruders, and the ALE layer defines the protocols for transmission of the ALE words. The following is an overall description of the functions at the FEC layer and the ALE layer:

The ALE words are transmitted with an 8-FSK serial tone waveform. The signalling speed is 125 symbols per second (baud) and therefore the data rate of the modem is 375 bits/s. The ALE word is divided into two parts, and a Golay code which doubles the number of bits is added to each of the parts. The two coded parts of the word are interleaved. The word, which is now 48 (actually 49) bits is transmitted three times to combat noise, interference and fading. (When calling the word is transmitted several times.) This type of “triple word” takes 392 ms to transmit. The combination of the use of FSK and the data rate do not make the link set up particularly robust at low SNR. Thus the linking can be less robust than the traffic transmission if low rate PSK modulation is chosen for the latter. This is a disadvantage and is one of the reasons why 141A was not chosen as a NATO standard. In 3G automatic radio systems (STANAG 4538 and 141B Appendix C), the waveform used for linking is more robust than the traffic waveform.

Linking Protection can be used to protect the ALE signalling against intruders. If such protection is required, it shall be performed in accordance with Appendix B of the standard. This involves scrambling of the ALE words, which means that the bits are encrypted with a prescribed encryption key. In the 141A version from 1992 and later, Link Protection is described in more detail in Appendix B.

All ALE stations shall be capable of storing 20 self-addresses each with a length of 15 characters. The characters are obtained from an alphabet of 38 characters. Individual stations, groups and networks can be called up, and calls which do not require a reply can also be made.

ALE stations can scan a selection of frequencies at a rate of either 2 channels per second or 5 channels per second (10 channels per second is optional). 141A is an asynchronous system, in other words no prior knowledge is needed of the ALE station(s) to which an ALE call is to be made. If a calling station knows that the receiver is on a given channel, it makes a short call on

that channel and a link is established by means of three-way handshaking. If the receiver scans many frequencies, the call is repeated for a sufficient time on the selected channel that the receiver must pass through the actual frequency in its scanning cycle. If the transmitter makes a call to several stations (a group or network call), the receivers reply in time slots (TDMA). After the establishment of the link, a timer starts, and if traffic is not detected in a certain time interval, the link is terminated.

As mentioned previously, a method exists for transmitting *data* by way of the ALE exchange itself. By using the CMD word, simple text messages can be transmitted using a set of 64 characters (AMD – Automatic Message Display). There are also two other optional message protocols which can be used to transmit data; DTM (Data Text Message) and DBM (Data Block Message).

In contrast with STANAG 4538 and 141B Appendix C (3G), 141A prescribes procedures for assisting the frequency selection algorithm (ACS –Automatic Channel Selection). ALE stations shall periodically transmit sounding signals, which are one-way signals and do not require a reply, consisting of an ALE word providing identification of the transmitter. Those stations which hear the sounding analyse and store information about the quality of the signal received (LQA - Link Quality Analysis). LQA can also be performed on the basis of ordinary ALE traffic, not only based on the sounding signal. Typical information stored in the LQA memory is BER and SNR; multipath measurement is optional and rarely used. Frequency selection is made on the basis of the information stored in the LQA memory. This information can also be exchanged between ALE stations by means of the ALE word “CMD”. The standard also contains a description of an optional two-way LQA exchange protocol.

## **12.2 Mil-Std 188-141B**

This standard is a new edition of Mil-Std 188-141A, with the same title, but with expanded and more advanced functionality. The organization of the standard is the same as for 141A, with the basic radio functions described in the main part, while references to Mil-Std 188-110 (or NATO’s corresponding STANAG standards) for modem functions and more advanced HF technology are described in a number of appendices. The automatic adaptive protocols described in 141A Appendix A have remained in place in Appendix A of 141B, and are here called “Automatic Link Establishment System (Second Generation (2G))”. Appendix B (Linking Protection) from 141A has also been retained in 141B. A number of new appendices have then been added. The following is a brief description of the contents of each appendix:

### **12.2.1 Appendix A: Automatic Link Establishment System**

This appendix is often referred to as Mil-Std 188-141B/A. The automatic, adaptive functions described here are called “Basic ALE” in 141B. If a radio system requires ALE, then Basic ALE *shall* be implemented, but 3G ALE, described in Appendix C, *can* be implemented in addition. The content of this appendix is largely the same as in Appendix A of Mil-Std 188-141A, but the

text has been significantly reorganised and rewritten, and two technical amendments should be mentioned:

1. There is a performance requirement on the detection of other specified signals in a channel before transmission is initiated (“listen before transmit”).
2. An optional, alternative ALE protocol, “Alternative Quick Call AQC -ALE”, is also defined. An ALE controller which is equipped with this will always listen in normal ALE mode, and can respond to normal ALE calls, but can also initiate and respond to AQC calls, resulting in significantly shorter link time. The probability of linking shall be the same as for normal ALE. To achieve this, AQC has a fixed, compact addressing structure, the ALE words are built up in a slightly different way, and two of the words have been replaced by different words. Group calls are not possible in AQC mode, and neither is the exchange of data during link set up (AMD, DTM, DBM).

### 12.2.2 Appendix B: Linking Protection

For 2G ALE, the Linking Protection algorithm is unchanged compared with that described in 141A from 1992. Additional Linking Protection algorithms have been introduced for 3G link set up as defined in STANAG 4538 or Appendix C of this standard. These algorithms have not been tested.

### 12.2.3 Appendix C: Third generation automation of HF link

This is the appendix which is most commonly associated with 141B. It is almost identical with STANAG 4538, and contains third generation automatic radio functionality, referred to as “3G ALE” in the standard. 3G ALE can be implemented in addition to basic ALE defined in Appendix A which is mandatory. Details of Appendix C can be found in the description of STANAG 4538. One major difference from STANAG 4538 is:

- Fast Link Setup (FLSU) is not defined in 141B Appendix C, only Robust Link Setup (RLSU). RLSU is hence the only link setup mode providing interoperability between STANAG 4538 and 141B.

### 12.2.4 Appendix D: HF radio networking

If networking functions are required for an adaptive HF system, the protocols described in this appendix shall be used. By networking functions is meant routing, which means that the radio system is capable of routing messages indirectly when it is impossible to achieve direct links. The routing can have different degrees of complexity, from a simple protocol in the radio itself which can only route between the various connections to the radio, to complex protocols in a separate network controller which route traffic between different radios (often a multimedia gateway). The latter type uses dynamic routing tables and quality matrices separate for speech and data traffic. Examples of networking functions are: “Message store and forward”, “Automatic message exchange” and “Connectivity exchange”. Network management functions are also necessary, and Appendix D defines and recommends a modification of the Simple Network Management Protocol (SNMP) used in the Internet environment, known as HF Network Management Protocol (HNMP). HNMP is an application protocol at layer seven of the OSI model.

In the description of 3G automatic HF (Appendix C), it is mentioned that implementations should have a network management interface.

The networking technology in Appendix D was developed long before the recent research in mobile ad-hoc networks (MANETs), and will likely be replaced with MANET-driven protocols in the next release of the standard.

#### 12.2.5 Appendix E: Applications for HF radio networks

If the HF radio system is to provide the services described in this appendix, the protocols described or referred to here must be implemented. The actual applications are Internet applications which shall be capable of transmission through an HF subnetwork. The appendix describes how these can be implemented to make use of the HF subnetwork. Examples of Internet applications mentioned are: E-mail (described in detail), file transfer (FTP), remote log-in (TELNET) and hypertext (HTTP). For the last three of these, reference is made to RFCs in the Internet environment. The possibility of a later description of other applications such as digital image transmission and digital speech is also allowed for.

If the applications mentioned in this appendix are selected, the HF subnetwork *shall* consist of:

1. The HF radio parameters from the main text of Mil-Std 188-141.
2. 2G ALE as described in 141B Appendix A and Appendix G *or* 3G as described in 141B Appendix C.
3. Subnetwork interface as described in STANAG 5066, Annex A.

Network functions as defined in 141B Appendix D are optional.

Two methods of running Internet applications over HF are described; either by using a gateway which completely translates “Internet language” to “HF language” at all OSI layers, or by equipping the HF radio with an interface layer to IP applications which directly map incoming IP packets on to the HF data link protocol (transparent IP). The HF radio is then able to read and understand IP addresses. The latter is the case with Harris’s RF-5800H radio.

A special HF e-mail application (HMTP-HF Mail Transport Protocol) is defined in this appendix. This is a modification of the Simple Mail Transport Protocol (SMTP) of the Internet, optimised for HF. It can be run with or without a transport protocol (TCP), but the optimal performance over an HF channel is achieved only by running without TCP, and this is defined as the interoperability mode for HF e-mail. HMTP must be “translated” to SMTP by a gateway. An alternative e-mail protocol is also described; CFTP – Compressed File Transport Protocol. This provides slightly faster delivery of e-mail than HMTP, but is not defined as the interoperability mode neither in the American nor in the NATO standards. It is Rockwell-Collins’s “HF Messenger” that has promoted the use of CFTP. If several e-mail applications are implemented, the system shall be capable of receiving the different types simultaneously. These protocols are intended to be identical to those now described in STANAG 5066, and this appendix may in future revisions simply refer to that STANAG.



### 12.2.6 Appendix F: Techniques for anti-jamming and anti-interference

This appendix contains the specifications for *frequency-hopping 3G* automatic HF. Frequency hopping will protect the communication against jamming and interference. Reference is made to Mil-Std 188-148 “Interoperability Standard for Anti-Jam (AJ) Communications in the High Frequency Band 2-30 MHz” which forms the basis of the frequency hopping mode, whilst this appendix describes how 3G, with its link protocol and synchronous/asynchronous mode can be implemented in this hopping mode. The hopping takes place at a higher rate than the scanning of frequencies in 3G. For example, the appendix describes how linking can take place *before* or *during* the hopping and how 3G PDUs can be spread over several hops.

### 12.2.7 Appendix G: HF data link protocol

2G ALE as described in Appendix A provides a possibility of transmitting data (not just link establishment) through its AMD, DTM and DBM protocol. However, these give inferior transmission capacity, and better performance can be obtained by running 2G ALE, a data link protocol and the modem protocols described in Mil-Std 188-110. This appendix describes a data link protocol for use in 2G HF in conjunction with Mil-Std 188-110. The data link protocol selected is STANAG 5066, so reference is made to this standard.

### 12.2.8 Appendix H: Management information base for automated HF radio networks

This appendix is closely associated with Appendix D and defines a Management Information Base (MIB) for automatic HF networks. An MIB contains definitions of data objects which shall be handled by a network management program. A modified version of the SNMP protocol used in the Internet environment has been chosen for management of the HF network. This is HNMP, as defined in Appendix D.

The original intent of this Appendix was to provide a core MIB for features common to all systems, and that manufacturers would then provide extensions to manage their unique features. In practice, most manufacturers have chosen to provide complete MIBs for their systems that stand alone, so this appendix may be eliminated in future revisions of Mil-Std-188-141.

Mil-Std 188-141B describes how a complete system can be put together ranging from Internet applications or “HF close” applications to radio functions in order to transmit speech and data over an HF network. Many of the components of this system are optional, and hence are not required to run in interoperable mode. But if the functionality they provide is required, then the protocols defined in this standard *shall* be used. The standard opens for further expansion to add new functionality in the future.

## 13 STANAG 4444

The title of this standard is “Technical standards for a slow-hop HF EPM communications system”, and it was released in 1999 after eleven years of work (!). This was the first standard

that was initiated in the AHWG in 1988. It has raised many discussions, such as what the real threat to HF systems is (was), how difficult the channels at high latitudes really are, and the need for automatic radio systems. The work of the AHWG with this standard has led to a series of spin-offs, such as the DAMSON project (analysis of the channel conditions at high latitudes) and a number of other STANAGs which have been produced along the way; STANAG 4415, STANAG 5066, STANAG 4538 and STANAG 4539. During the first years of development of this standard, various systems from different countries and vendors were presented and there was a certain amount of contention to promote the different systems (which involved both wine-tasting, dinner cruises and visits to the Moulin Rouge for the members of the AHWG!). Following the withdrawal of the US from the NATO group (in about 1995), representatives of the German and French industry eventually collaborated to produce the STANAG document. After some time, the US returned to the AHWG, but was never again involved in the development of STANAG 4444. The STANAG was originally classified as secret but became declassified in 1998.

STANAG 4444 has to date been ratified by a sufficient number of nations (including the US even though they have their own Mil-Std 188-148), and NATO has decided to promulgate it. The standard is intended for tri-service use.

Telefunken Racoms has implemented the STANAG for use by the German Navy. In France and in Italy there is a joint implementation effort sponsored by the MODs where the work load is shared between Thales, France and Selex Communications in Italy. The French/Italian effort will result in implementations on different platforms including a software defined radio platform. During implementation, the companies have cooperated on clearing up uncertainties in the STANAG, and these have been reported to the AHWG for inclusion in a future version of the STANAG. When the French/Italian implementation is ready, there are plans for interoperability testing with Germany.

STANAG 4444 is the only HF standard mandating a crypto algorithm to be used. The crypto algorithm selected is the Saville algorithm. There have been long discussions in the AHWG whether this algorithm will be supported in the future, and whether the selection should be changed to the Medley or the AES algorithm. There is no clear way ahead on this issue at the moment (2006), but it is likely that there will be a new annex on information security in a new edition of the standard.

### **13.1 Technical description**

The STANAG is a slow frequency hopper (8.88 jumps per second) which shall provide protection of communications against deliberate jamming and unintentional interference (blocked channels). It shall also provide communication under difficult channel conditions (low SNR, Doppler and multipath spread) and a combination of blocked channels and difficult channel conditions.

It covers the functions at the lowest layers of the OSI model including radio functionality; hence it does not refer to STANAG 4203 as the other standards do. The standard does not include layer three (the network layer) of the OSI model in the traditional sense (routing). However, the AHWG identified some services which are necessary in an HF network, and in the absence of a suitable OSI model layer in which to place these services, the standard defines them as belonging to the network layer. STANAG 4444 operates in single-tone mode and half-duplex.

An HF EPM radio in accordance with STANAG 4444 can be run in two different modes: Multi-application mode (MA mode) or TDMA mode. The mode is selected by the operator before initialisation. The TDMA mode has been designed with Link 22 (NILE) in mind. STANAG 4444 can be integrated with other HF systems into a single radio, which will then be capable of receiving both STANAG 4444 and other types of traffic if operated in MA mode. This is made possible by dividing up the listening time into two intervals, one dedicated to 4444 traffic and the other to other types of traffic.

Many types of traffic can be transmitted by means of STANAG 4444: digital speech and data traffic, including ACP formatted data messages, telefax, teleprinting, BRASS (Broadcast And Ship-Shore) and Link 22 (NILE). The data traffic is divided up into three types: data continuous, data message of variable length (files or data packets), and data message of fixed length. Table 13.1 shows the connection between the type of data traffic and the type of link and link access mechanism for the individual traffic types.

Types of logical links are Point-to-Point (PtP), Point-to-Multipoint (PtM) and an implicitly addressed link which does not contain a link set up, but where the radios which are to receive the traffic are pre-arranged. The latter type of link is only used in the TDMA mode which transmits data messages of fixed length.

Two types of link access are incorporated in STANAG 4444: random access (in MA mode) and TDMA. In the case of random access, a single call is made on the selected channel without prior information on whether the channel is occupied or not. For PtM, STANAG 4444 defines only one-way link set up, that is, the transmitter does not receive confirmation that the link set up has succeeded. In comparison, STANAG 4538 defines a two-way PtM link set up.

Links	Link Access Procedures	TRAFFIC				
		Digital voice	Data continuous	Data Message		
				Variable length		Fixed length
				with interleaving	with ARQ	
Explicitly addressed PtP	LSU with ACK	X	X	X	X	
	One-way LSU	X	X	X		
Explicitly addressed PtM	One-way LSU	X	X	X		
Implicitly addressed	TDMA					X

Table 13.1 Types of link and link access used for different types of traffic

The different types of logical links are used to establish communication links which represent the ways in which communication takes place. The STANAG divides up the communication links into:

- unidirectional (PtP and PtM)
- conference (several successive PtPs or PtMs)
- TDMA

### 13.1.1 Physical layer

We will now describe in broad terms the functions layer by layer, beginning with the physical layer.

A multi-waveform concept is fundamental to the STANAG, similar to that of STANAG 4538. Six different waveforms are defined which are all designed for optimal performance under different channel conditions, percentage of blocked channels and with different throughput and reliability requirements. All use PSK modulation (2, 4 and 8-PSK). Five of the six waveforms belong to the class of Equalizer Enhanceable (EEWF) waveforms. These transmit alternating sequences of data and training symbols and use equalisation in the receiver to combat distortion. Reed-Solomon coding and convolutional interleaving are used for these waveforms. The least robust EEWF (EEWF5) was produced specially for Link 22 (NILE) and gives the best information throughput at 2400 bps. The most robust EEWF (EEWF1) can give 75 bps data rate with 75% blocked channels, Doppler spread of 1 Hz, multipath spread of 10 ms and a sufficient SNR for this data rate. MA mode and TDMA can use all these EEWF waveforms. In the TDMA mode, the waveform must be decided beforehand.

The remaining waveform belongs to the class of Direct Sequence (DSWF) waveforms. This class contains a synchronisation sequence and user data encoded with Walsh sequences. Convolutional coding and block interleaving are used with this waveform. The data rate is only 75 bps, but this is the most robust waveform in combating channel distortions (with a moderate number of blocked channels). DSWF is used only in MA mode.

EEWFs provide higher data rates than DSWF, but are less robust with respect to channel conditions. However, they can provide better performance than DSWF when a high percentage of the channels are blocked. EEWFs 1 to 4 and DSWF have the same signature on the air, while the signature of EEWF5 is unique. New waveforms may be included in the future.

At the physical layer, this STANAG defines hop structure, waveforms and radio characteristics. The modulation types are different forms of PSK. Radio characteristics such as frequency accuracy, switching times etc, are stricter defined than in STANAG 4203. By “hop structure” is meant the frame composition within each hop, in other words the order and length of, the synch, training and data sequences. One hop lasts 112.5 ms and contains 270 symbols which are transmitted at a rate of 2400 symbols per second. At the beginning of each hop, a certain number of “flush” symbols are sent, so that the radio equipment has time to change frequency. Then, alternating sequences of data and training symbols are transmitted within a hop, with differing ratios for the different types of waveform. DSWF is very similar to the waveform of STANAG 4415.

### 13.1.2 Data link layer

The data link layer takes care of link set up and link release and the exchange of the different types of traffic between two nodes. In both MA mode and TDMA mode initial network parameters (for example a frequency list) are needed in order to participate in communication with other HF stations in a network. These are obtained from a local PC by remote control, or may be stored in a memory.

When an HF EPM node is not transmitting or receiving, it is in search state. It then hops at a rate equal to or less than the basic hop rate of a transmitting node. The hop rate in the search state is the basic hop rate divided by certain discrete numbers between 1 and 192. In this way the searching node can achieve hop synchronisation and can receive a call.

Link set up can be achieved in two ways; by using EEWF2 where one Call Synch Word (CSW) is transmitted per hop a certain number of times, or by using DSWF1 and transmitting one CSW which extends over 48 jumps (which is more robust). A CSW contains information about, among other things, the type of communication link, priority, waveform, FEC/interleaving, application identifier and Time-of-Day quality of the transmitter. LSU can be one-way or two-way with a returned ACK (PtP only).

The traffic types mentioned above use different waveforms at the different data rates. The ARQ protocol used for data messages of variable length in a PtP connection uses selective ACK, some type of code combining and no interleaving of the waveform. The data message is divided up so that a single data packet in combination with a sequence number and Reed-Solomon code redundancy fit into a single hop. A certain number of packets are transmitted before a selective ACK is returned. If a data packet is not acknowledged, the same packet is transmitted a second time with the same coding. Some type of “code combining” is used in the receiver to decode the packets. In STANAG 4538, a more efficient code combining is described in which *different* coded versions of the packet are transmitted and combined. Finally, an End-Of-Transmission (EOT) packet is transmitted. A time-out is defined both for the transmitter and the receiver so that if no data is received or acknowledged, search state is resumed. The receiving node can also request retransmission from a given sequence number.

In TDMA mode, neither link set up nor EOT are used, since each participating node has a certain time interval in which it can transmit.

### 13.1.3 Network layer

In this STANAG, functions such as timing structure, address management, frequency management, Time-Of-Day (TOD) management and “net services” are located at the network layer. As mentioned previously, these are not traditional network layer functions in OSI terms, but belong more naturally to the concept of network “management”. STANAG 4444 describes these management functions in considerable detail.

The timing structure of an HF EPM network is based on Net Reference Time provided by GPS. Each node in the network does not need to be equipped with GPS, but can have its time reference updated from a central node which has GPS time. The timing structure is naturally different for MA mode and TDMA mode.

In MA mode, the time is first divided up into two time slots, designated time slots 1 and 2. This division of time applies only when a node is in search mode, and slot 1 is dedicated to searching for HF EPM calls, while slot 2 is dedicated to calls from other HF systems. Time slot 2 can be equal to zero if this is specified in the initial network parameters. The duration of the time slots is at least 5.4 seconds, and can be considerably greater. The smallest time unit in the system is a hop lasting 112.5 ms. A service interval is defined as 48 jumps (=5.4 s) and each service interval within time slot 1 shall contain one or two service windows. One of the service windows is the last three jumps in each service interval; this is the synchronous service window which provides for the synchronous network services. An asynchronous service window which provides for asynchronous services *may* exist at the beginning of each service interval, and the size of the window and visitation rate are specified in the initial network parameters. We will return to the type of net services that exist.

In TDMA mode, time is divided up into a network cycle structure, each unit of which is assigned a certain number of jumps.

We will not deal with address management here.

#### 13.1.4 Channels and frequency management

A channel is defined in STANAG 4444 as a time-varying succession of frequencies. For MA mode there are two channel types: *Service channels* which are used for the net services, and *main channels* which are used for searching, link set up, traffic and a few net services. Then there are two types of service channels: Synchronous service channels and asynchronous service channels, which are used in the two cases described in the last section. There are three types of main channels: General search channels, CONF search channels and traffic channels. In TDMA mode, only traffic channels exist.

STANAG 4444 does not describe which methods to use to find frequencies in a hop set (prediction, interference, etc). Nevertheless, such limitations as forbidden frequency bands, maximum hop bandwidth, and so on, can be specified in the initial network parameters. The hop set is defined either deterministically or by means of a TRANSEC algorithm which depends on the Word-of-Day (WOD), Time-of-Day (TOD) and the net address. The hop set can contain up to 1024 frequencies. The hop set is generated by the same process at all the nodes in the HF network so that they are always in agreement regarding which frequencies to hop at. The frequency for each hop is selected randomly according to a TRANSEC/NETSEC algorithm. If the hop set contains only a single frequency, the system can hop at that frequency, but this is inefficient. An alternative way in which an HP EPM radio can operate at a fixed frequency is by using time slot 2 and other waveforms such as STANAG 4285 or STANAG 4539.

#### 13.1.5 Time-Of-Day management

An HF EPM network has a Net Time Reference given by GPS and described in detail in STANAG 4430 [5]. The time given by the internal clock at each HF node in a network must be as close to the Net Time Reference as possible. In *centralised* TOD management, a Master Node is assigned which is responsible for keeping the other nodes updated with respect to TOD. These can achieve accurate time setting by using five different TOD net services as illustrated in Table 13.2. *Distributed* TOD management is used when *the majority* of nodes in the network have their own accurate time setting (for example GPS). A node which does not have accurate time can obtain this by enquiring of a node which does.

#### 13.1.6 Net services

“Net services”, which in our opinion should rather be called “management functions”, deal with minor irregularities in a network. They normally use synchronous or asynchronous service channels, meaning that at specified times (service windows) the hop set is changed and the services can be carried out. The majority of net services use synchronous or asynchronous service channels, but some net services can take place in the main channels. Some net services can time-share the same channel. All net services are defined for the MA mode only, and not for the TDMA mode. They use the EEWF2 waveform, whose advantage is the ability to handle distortion in the channel.

The net services which is provided by an HF EPM node in the various operational modes are shown in Table 13.2. The colour code used for the net services is as follows:

- **Red**: The net service uses a synchronous service channel
- **Purple**: The net service can use both a synchronous service channel and one or more of the main channels
- **Blue**: The net service uses a main channel (the search channel)
- **Green**: The net service uses an asynchronous service channel

The various net services are as follows:

Break-in (BI): The user of this service can break into an ongoing communication and transmit traffic of higher priority to HF EPM nodes which provide this service. There are three sub-types of BI.

Late Traffic Entry (LTE): The user of this service has knowledge of the initial network parameters and can acquire knowledge of the necessary link parameters to be able to synchronise and receive ongoing traffic.

Time-of-Day (TOD) distribution: The user of this service has an inaccurate time setting and can improve this relative to the Net Time Reference by contacting another participant in the network with a more accurate clock. Normally this unit is a master node which is specially intended to provide this service.

Late Net Entry (LNE): The user of this service does not have knowledge of all the initial network parameters, but can obtain these and become a member of the network by contacting a special node, the Net Management Unit, which provides this service.



Operational modes (of the PU providing the service to the user of the service)		AVAILABLE NET SERVICES									
		BI Services			Late traffic Entry	TOD Distribution					Late Net Entry
		BI in CONF	BI with ACK	BI without ACK		Passive acquisition	Beacon distribution	Sync request/answer (2-way)	Sync request/answer (3-way)	Async request/answer	
MA MODE	General Search	NO	YES	YES	NO	NO	YES	YES	YES	YES	YES
	CONF Search	YES	YES	YES	NO	NO	NO	NO	NO	NO	NO
	LSU	YES	YES	YES	NO	YES	YES	NO	NO	NO	NO
	Digital Voice	YES	YES	YES	Possible	YES	YES	NO	NO	NO	NO
	Data Continuous				YES						
Data Message with interleaving	YES										
Data Message with ARQ	NO										
TDMA	Data Message fixed length	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

Table 13.2 Available net services in the various operational modes

### 13.1.7 Security

Two types of security shall be incorporated in systems running STANAG 4444: TRANSEC and COMSEC. TRANSEC protects technical information about the actual communication, for example synchronisation sequences or frequencies, to prevent detection and jamming of the communication. Frequency hopping is the dominant TRANSEC algorithm in STANAG 4444. COMSEC protects the actual data transmitted so that the content cannot be compromised. Encryption shall take place after coding and interleaving. Both TRANSEC and COMSEC shall be internal algorithms in the EPM radio. The input to both types of security mechanism is WOD (Word-of-Day) and MI (Message Indicator). MI is not transmitted over the air; it is implicit, that is, derived from the TOD (Time-of-Day) and the address field. There are several WODs which

are used in different contexts. They are specified in the initial network parameters which must be known in order to participate in the network.

## 14 EW PROPERTIES OF THE HF WAVEFORMS

When using HF communications, as all other radio communications, the EW (electronic warfare) aspect should be kept in mind. Third parties with suitable receiver equipment can detect our transmissions and their origin, and also obtain certain information about the type of communications system in use. Avoiding this is called LPI – Low Probability of Intercept. In this section we give some general comments regarding EW, in the light of the standards described in this report. We will not discuss STANAG 4444, which is designed to have good characteristics in this respect, but concentrate on the other standards.

The first step for an EW receiver is to detect that a signal is being transmitted at a given frequency. In this context the appearance of the signal on a spectrum analyser should be considered. All the serial tone waveforms (PSK and QAM) with 2400 baud symbol rate have more or less the same power spectrum: The power is evenly distributed over a 3 kHz bandwidth and resembles white noise in this band (the precise shape of the spectrum is determined by transmitter filtering). Hence, these waveforms are in principle relatively difficult to detect at low SNR. On the other hand, in the case of parallel tone waveforms (appendix to Mil-Std 188-110) and FSK waveforms (2G ALE), distinct frequencies will appear in the spectrum, making them easier to detect. Of course, it is also generally the case that signals are more difficult to detect if they are transmitted at low power. Hence the use of low rate waveforms such as STANAG 4415 can not only be considered as a means of improving the robustness of the communication at a given transmission power, but it is also possible to reduce the transmission power to make hostile detection more difficult. The disadvantage of this is that it is necessary to be on the air longer to transmit the same amount of information, which in turn increases the probability of detection. Hence there is a trade-off here, but for short messages it will be wise to use a robust low-rate waveform and transmit with the lowest possible power.

The next step is recognition of the waveform in use. This is a prerequisite for being able to decode the message, but it also provides information about the type of unit communicating (e.g., it can be assumed that only the most advanced units have the most modern waveforms available). As mentioned above, the PSK and QAM waveforms look the same at a spectrum analyser, but it is possible to distinguish between PSK and QAM by studying the histogram (estimated probability distribution) of the signal envelope (the amplitude). PSK has a constant envelope, while QAM has a varying envelope. If the channel is time varying (fading), this distinction is obscured. Another tool which can be used for recognition is correlation analysis. The autocorrelation of the signal exhibits rapid periodicities, for example due to known sequences, which are characteristic for each individual waveform. It is at least as important that the known sequences are actually publicly available (the standards are unclassified), so that correlating the signal with known sequences from different standards is possible. This can also be used to detect signals which are invisible on a spectrum analyser because they are below the

noise floor. This contradicts the statement in the previous section that serial tone waveforms are *in principle* relatively difficult to detect.

Burst waveforms (such as STANAG 4538) have standardised duration and can therefore be recognised on the basis of their duration. On the other hand, the short duration of certain burst waveforms will make them more difficult to detect using a receiver which monitors several frequencies, and therefore is not able to listen for a very long time at each frequency.

Regarding the actual content of the message, this will often be encrypted, but one should nevertheless be aware that if the headers at some level of the protocol stack are not encrypted, they will contain addresses which can be used to derive the identity of those communicating. One should also bear in mind the possibility of traffic analysis, for example it can be assumed that a station which transmits very large amounts of traffic is a central element of the communication system.

In concluding this discussion we can say that there is always a trade-off between increased data rate/capacity and EW characteristics, which is easily forgotten as a result of all demands for higher data rates. In general, the less data that is transmitted, the easier it is to be concealed, and an operational assessment must be carried out in each individual case.

## 15 SUMMARY AND OUTLOOK

The HF House consists of a number of standards that reside at the physical layer and the data link layer of the OSI-model. The interface to actual applications that wants to connect to the HF subnetwork is also defined within the HF House. This report has briefly described the main functionality of the various standards and also the relations between the different standards. This last section gives some historical review of the development of the standards and also some viewpoints on the status today as regards interoperability and the procurement process.

The development of the different HF standards has followed different routes. The US were ahead of NATO by the end of the eighties with their Mil-Std 188-100 series of standards for long haul communications that also included HF. In NATO only STANAG 4197 for digital speech and STANAG 4285 existed, the latter was defined in the late eighties when NATO realized that it needed a standard also for data transmissions over HF. There were plans for further development of STANAG 4285, but when the AHWG was formed, the work was started from scratch.

In the process of defining a robust waveform, STANAG 4415, and a high data rate waveform, STANAG 4539, several candidate waveforms from different vendors were suggested and tested on the same simulator at DERA, UK (now QinetiQ). For both standards American/Canadian waveforms were selected based on the test results.

A subgroup of the AHWG with many nations present, worked on the development of the ARCS standard, STANAG 4538. Work and ideas from different vendors and academia were presented and merged into the final standard document with the US as editor. In this process there were no competition between different candidate systems.

In the work with the HF EPM standard, STANAG 4444, the US withdrew from the AHWG at one point. Representatives of the German and French industry then worked together over several years in producing this standard. STANAG 4444 is probably the most complex standard, and to date two implementation efforts are known; one by Telefunken Racoms in Germany (the most mature) and one joint effort by Thales France and Selex Communications in Italy.

NC3A (former STC) played an important role in the development of BRASS in NATO. BRASS needed an efficient HF protocol for both broadcast and ship-shore communication. The NC3A participated in the AHWG, but the relative slow process in NATO and NC3A's impatience of finishing a standard resulted in the development of a data link protocol at NC3A which later became STANAG 5066. One basis for the development of this data link protocol was the utilization of fielded equipment such as STANAG 4285 modems and cryptos. STANAG 5066 has great success and is also referred to in the American Mil-Std 188-141B.

Some of the STANAG's in the HF House represent older technology, and will not be procured to any extent in the future. This applies to for instance STANAG 4285 which lacks auto baud and is therefore less efficient together with a data link protocol, and STANAG 4197 which will soon be replaced with a new standard, STANAG 4591.

2G automatic radio systems (STANAG 5066, Mil-Std 188-141A and the waveforms in STANAG 4539) has been fielded to a large extent and it is expected that this technology will be a main resource in NATO for HF communications. However, 3G automatic radio systems have shown superiority over 2G regarding linking time and robustness, so 3G technology will gain terrain and coexist with 2G in the future. The Bowman project in the UK has procured 10 000 3G HF radios. For the first Cluster of the JTRS program in the US only 2G HF systems have been selected, but work is being done to also include 3G for later Clusters.

The future of STANAG 4444 is uncertain. Two implementations are under way, one in Germany and one in France/Italy. There is a question whether frequency hopping is efficient at HF. Frequency hopping has its advantages under certain channel conditions, but there may also be co-location problems. For a slow-hopping system such as STANAG 4444, the LPI protection is not particularly high and probably not the reason for selecting such a system.

The STANAG's 5066, 4538, 4444 and Mil-Std 188-141B are very complex. Implementation of complete versions of these STANAG's takes years. Therefore, the vendors implement these standards stepwise, and sell their products underway with only partial implementations of the standards. The vendors also make deliberate choices of not to implement certain parts of the standards as they consider that part of the STANAG as less cost effective. For instance, Harris

Corporation has to date not implemented Robust Link Setup in their STANAG 4538 implementation and it is not likely that they ever will. Thales has not implemented Group Calls in their Mil-Std 141A product.

It has been suggested in the AHWG that different levels of standard conformity can be introduced for the complex standards. That means that an implementation could be classified to a certain STANAG conformity level which would guarantee that certain parts of the STANAG were implemented and that interoperability would be achieved to a certain level. The number of possible levels would reflect the complexity of the standard. This suggestion has not so far been adopted by the AHWG.

As long as official standard conformity levels do not exist, procurement agencies should make an effort to write specifications in such a way that the tenders are forced to point out where their product deviates from the standard. In this way, the procurement agency will become aware of functionality that may not be present in a certain product.

Standards are developed to obtain interoperability. However, interoperability between different radio products is by no means guaranteed with the complex standards at HF. Probably is interoperability guaranteed at some level, but not necessarily at a high efficiency level because implementation choices made by the vendors play an important role in this aspect. It is therefore important that in a procurement process, requirements are set on testing and certification of radio equipment at recognized test institutions. Without such certification, efficient radio communications and at the same time interoperability are not guaranteed.

Except for the STANAG 4444, security aspects such as COMSEC and TRANSEC have not been an issue in any of the HF standards. This may be a fundamental problem to achieve interoperability between nations. Without interoperable crypto systems, interoperable waveforms and protocols may be useless.

## APPENDIX

### A.1 Glossary

ACK – Acknowledgement  
ACP – Allied Communication Publication  
ACS – Automatic Channel Selection  
AHWG – Ad Hoc Working Group  
ALE – Automatic Link Establishment  
ALM – Automatic Link Maintenance  
AMD – Automatic Message Display  
ARCS – Automatic Radio Control System  
ARQ – Automatic Repeat Request  
BER – Bit Error Rate  
BI – Break In  
BRASS – Broadcast And Ship-Shore (NATO project)  
BW – Burst Waveform  
CNSC – Communication Network Sub-Committee  
COMSEC – Communication Security  
CONF – Conference  
DAMSON – Doppler and Multipath Sounding Network  
DPSK – Differential Phase Shift Keying  
DSWF – Direct Sequence Waveform  
DBM - Data Block Message  
DTM – Data Text Message  
EPM – Electronic Protection Measures  
EEWF – Equalizer Enhanceable Waveform  
FEC – Forward Error Correction  
FLSU – Fast Link Setup  
FSK – Frequency Shift Keying  
FTP – File Transfer Protocol  
HDL – High-throughput Data Link protocol  
HTTP – Hyper Text Transfer Protocol  
IP – Internet Protocol  
ITU – International Telecommunication Union  
JTRS – Joint Tactical Radio System  
LDL – Low-latency Data Link protocol  
LPI – Low Probability of Intercept  
LQA – Link Quality Analysis  
MELP – Mixed Excitation Linear Predictive (speech coding)  
NC3A – NATO Command Control and Communication Agency  
NILE – NATO Improved Link Eleven  
PDU – Protocol Data Unit  
PSK – Phase Shift Keying  
PtM – Point-to-Multipoint  
PtP – Point-to-Point  
QAM – Quadrature Amplitude Modulation  
RATT – Radio And TeleType  
RFC – Request For Comments  
RLSU – Robust Link Setup  
SNMP – Simple Network Management Protocol  
SNR – Signal to Noise Ratio  
STANAG – Standard Agreement  
TCP – Transmission Control Protocol  
TFTP – Trivial File Transfer Protocol  
TDMA – Time Division Multiple Access

TOD – Time of Day  
TRANSEC – Transmission Security  
UDP – User Datagram Protocol

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