FFI RAPPORT

PERFORMANCE TESTING OF STANAG 4406 (MILITARY MESSAGING) USING IP OVER HF

JODALEN Vivianne, SOLBERG Bjørn, GRØNNERUD Ove, LEERE Anton

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8) ABSTRACT

This report is the final summary of a test activity of Project 822 SIGVAT HF. The STANAG 4406 (Military Messaging) and its tactical protocol profile has been tested over an HF link supporting IP. The automated HF technologies include the STANAG 4538 (3G HF), STANAG 5066 (2G HF) and HDL+, a data link protocol proposed for standardization. The work has been published in four international papers that are included as appendices in this report. This report references the papers, and add some results that have not been published. By using the S4406 Annex E protocol profile we have shown that a reliable message transfer is possible over an IP network which comprise an HF link. This opens for an architecture where the HF links may be directly utilized also for IP traffic from various other applications. Application Throughputs up to a few kilobits per second were achieved in our tests. However, an HF link will represent a potential "bottleneck" in an IP network and it requires special attention for optimum performance.

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CONTENTS

PERFORMANCE TESTING OF STANAG 4406 (MILITARY MESSAGING) USING IP OVER HF

1 INTRODUCTION

In the two first years of Project 822 SIGVAT HF at FFI, a main activity was to test the new STANAG 4538 (3G HF) (1) over-the-air. This work was a joint effort between QinetiQ in the UK, TNO-Telecom in the NL and FFI, and it has been documented in (2). An expressed goal of this test activity was to test IP over the new STANAG. In 2003 we saw the potential of combining the ongoing work on Military Message Handling Systems in another FFI - project; Project 840 STAROS, with our HF work. Since our two STANAG 4538 radios, the Harris implementation in RF-5800H, have a direct IP interface, and the STANAG 4406 (3) on formal military messaging may use IP as the networking technology, we decided to do some functional testing when connecting the application with the HF bearer service. STANAG 4406 was therefore used as a tool for exploring the IP capabilities of the radio and thereby fulfilling one of the goals of the 3G HF testing.

The initial functional testing developed to become a more thorough performance testing, and various aspects of the IP capabilities of the radio have been assessed. We also expanded the HF systems testing by including the 2G HF technology represented by STANAG 5066 (4) and the enhanced 3G technology represented by the HDL+ data link protocol proposed for NATO standardization by Harris.

During the work we have had good support by a Technical Assistance Agreement between Harris Corporation and FFI. In particular, Eric Koski of Harris has been very helpful and provided us with insight into complex technologies of their radio. For the STANAG 4406 application we have used the Thales XOmail implementation, and we have also received very good and expedient support from Thales Trondheim. In return, the two companies have received some new viewpoints and “bug-reports” on their implementations.

The results of our two years of work have been presented in various forums; the NATO BLOS COMMS Ad-Hoq Working Group, our projects Prosjektråd, and at conferences. There exist four international papers on the subject, and they are included in this report in Appendix A to D, in chronological order. Instead of repeating the contents of the papers in this report, we will refer to the most appropriate paper for a description of the specific topic. Some new / not published results are described in separate sections of this report. The four papers are listed here and can be found in the following publications:

Appendix A: IP over HF as a Bearer Service for NATO Formal Messages, *IEE Conference Publication No 493,* 9th International Conference on HF Radio Systems and Techniques, pp 19-24, Bath, UK, 2003

Appendix B: Military Messaging in IP Networks using HF Links, *IEEE Communications Magazine*, Vol 42, No 11, pp 98-104, Nov. 2004

Appendix C: On-air Testing and Comparison of 2G and 3G HF, *Nordic HF Conference Proceedings*, p 3.5.1, Fårø, Sweden, 2004

Appendix D: NATO Military Messaging in the Tactical Domain – performance issues of an HF channel, *RTO Symposium on Military Communications, Proceedings*, RTO-MP-IST-054, Rome, Italy, 2005

2 PROTOCOL STACK OF STANAG 4406 USING IP OVER HF

When connecting the S4406 application with IP over HF as the bearer service, the two complete protocol stacks (Annex C and Annex E) are shown in Figure 1. The best description of the S4406 application and the HF STANAG's can be found in the introductory sections of Appendix B.

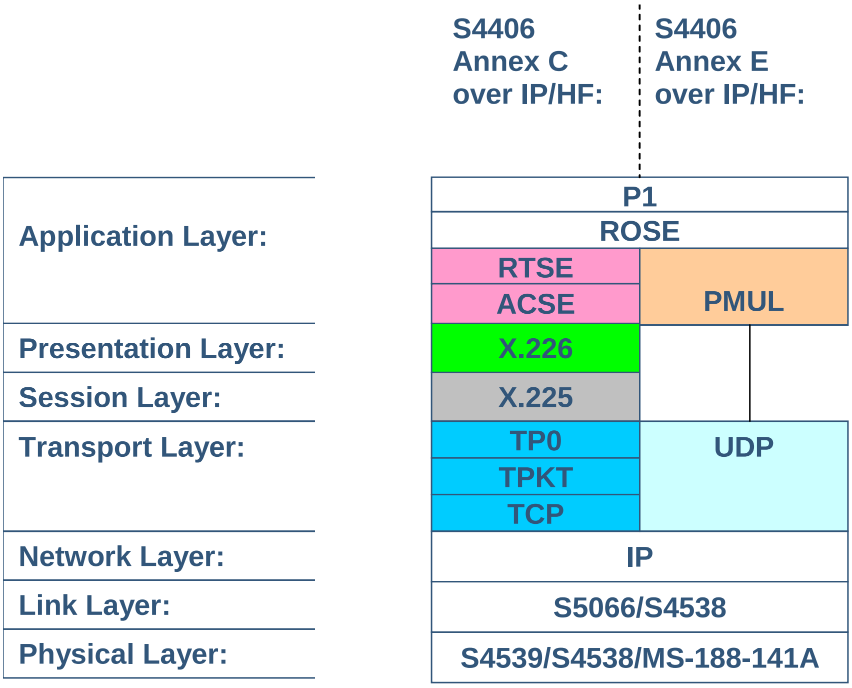


Figure 1 Protocol stack of MMHS (S4406) using IP over the various HF standards

3 IP OVER HF

A general description of a scenario where IP over HF is desirable and what the limitations are, is described in the introductory sections of Appendix B.

4 CONGESTION CONTROL ASPECTS

The lack of flow control/congestion control when the fast S4406 Annex E application is sending data packets to a slow HF radio is discussed in the section "Flow control aspects" in Appendix B. The shortcomings of the Source Quench technique and a proposal for a new congestion control mechanism are mentioned in section 6.1 of Appendix D.

Our experience with the RF-5800H and the firmware that we tested, was that a Source Quench packet was not sent from the radio until an overflow situation had occurred, and one packet had been discarded. This resulted in a NACK from the receiving application and a following retransmission. Harris has indicated that their implementation now sends a Source Quench packet *before* the overflow situation occurs, which will greatly improve the performance of the system, especially with respect to the vulnerability of P-Mul not receiving the last data packet of the message. We have not confirmed this new implementation of Source Quench.

5 MEASUREMENTS OF THROUGHPUT

We have used two definitions of throughput in our work. Most of our results are given as *Application throughput* which is the throughput experienced by the user of the messaging application when one message is sent at a time on a point-to-point link. It is defined in Figure 2. T_1 is the time when a message is sent from the message server, T_2 is the time when it is received by the receiving message server. At time T_3 the HF channel is released. *Data Link Throughput* is the true number of bits (including overhead) delivered by the HF service provider in a certain time period. Time for link setup is not included. We determined data link throughput by using an Ethernet "sniffer" counting transferred bytes and determining the transfer time from an oscilloscope on the HF channel. A formula for the relationship between application throughput and data link throughput is given at the end of section 7 in Appendix C.

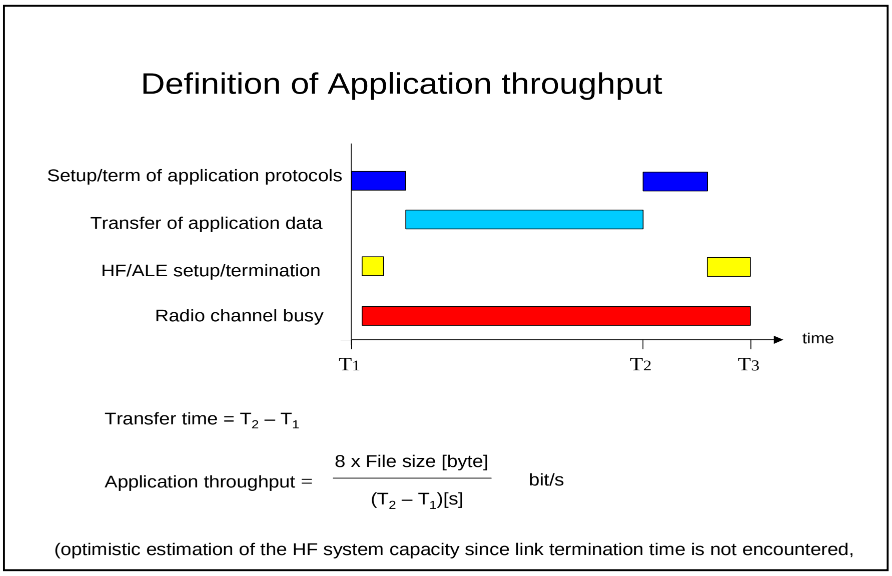


Figure 2 Definition of application throughput

5.1 The RF-5800H and its IP implementation of S4538

For IP traffic, the RF-5800H uses IP datagram concatenation and compression to enhance the throughput performance. This is discussed in Appendix A under “Throughput considerations and measurements”. An increased throughput efficiency is achieved by using these techniques, but this IP implementation will not necessarily be interoperable with other S4538 products, since these techniques have not been standardized. The NATO standardization group (BLOS COMMS AHWG) is now aware of this, and a standard for the IP interface is under development.

5.2 Comparison of the performance of S4406 Annex C and Annex E

Using the strategic, high data rate protocol profile defined in Annex C or the tactical protocol profile defined in Annex E over an HF link, is compared in Appendix A under “Throughput considerations”.

5.3 Throughput measurements on a point-to-point link in the lab

Our test setup in the lab is shown in a figure in section 7 of Appendix C for both the 2G and the 3G/HDL+ tests. The best description of these measurements is given in Appendix B under “Throughput Measurements”.

5.4 Throughput measurements on a point-to-point link over-the-air

A figure showing the test setup can be found in section 4.1 of Appendix D. The results are best described in section 7.2 of Appendix C.

6 IP MULTICAST

The lack of a standardized multicast packet data service in S4538 is pointed out in the “Multicast” section of Appendix A. This has been fed back to the NATO BLOS COMMS AHWG, and a proposal for a multicast protocol is now under development by the New Mexico State University.

However, the RF-5800H contains a non-standardized IP broadcasting service, on which a limited multicast service can be based. We have done some initial testing of the Multicast features of S4406 Annex E using this IP broadcasting service. This is described in Appendix D section 4.2. Using the broadcasting service of the RF-5800H, a fixed data rate has to be chosen in the radio. The data rate selected, is important for the probability of packet delivery. Figure 3 shows this probability of packet delivery versus SNR on the channel.

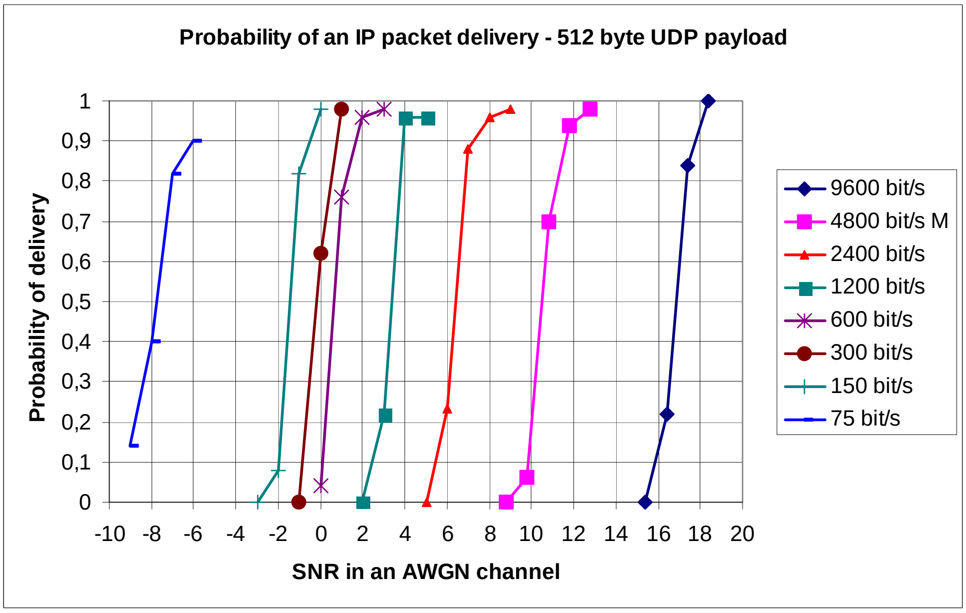


Figure 3 Probability of packet delivery for various data rates over a AWGN channel

7 COMPARISON OF THE PERFORMANCE OF S4406 ANNEX E WITH A DEDICATED HF MESSAGING APPLICATION

We here compare two applications used for completely different purposes, and the comparison may not be fair. We nevertheless thought it was interesting to quantify the penalty of introducing network functionality enabling an HF link to become an integrated part of the tactical internet. The dedicated HF messaging application is the Harris Wireless Messaging Terminal (WMT) using the Compressed File Transport Protocol (CFTP). The comparison is described in section 5.0 of Appendix D. A fair comparison between the two messaging applications could be possible if the subnetwork service interface of S5066 is used, and if a future version of XOmail would use the Service Access Point defined for S4406 messaging directly.

8 PROPOSALS FOR IMPROVEMENT OF THE P-MUL PROTOCOL (ACP-142)

Some shortcomings of the P-Mul protocol used in the S4406 Annex E profile have been identified, and are being worked on by NATO and the CCEB. Section 6.0 of Appendix D give an overview of the shortcomings and which solutions that will be proposed in edition 2.0. In addition to the proposals mentioned in Appendix D, pre-emption is also proposed in the new edition of P-Mul. This means that if P-Mul is processing a message, and a message of higher priority needs to be sent, the processing of the first message is temporarily stopped to allow immediate processing of the highest priority message.

9 IMPLEMENTATION ISSUES

We have noted several implementation choices that influence the performance that we have been measuring. Our results are only indicative of what can be obtained using these standards. We mention some of these implementation choices in section 5 of Appendix C.

During the period of testing, we have discovered a few "bugs" or shortcomings of the XOmail product. We have had a good dialogue with Thales Trondheim, and they have immediately provided us with patches that fixed the problems. According to Thales Trondheim, all the patches that we have received, have been incorporated in XOmail Version 11.3.

Similarly, we have had a dialogue with Harris Corp. We have received upgrades of the radio firmware along the way, and most of the tests have been conducted with a MP026 radio configuration. Their radio firmware V 1.3 and the WMT Version 6.0 should contain fixes to problems that we have discovered. FFI has not tried to confirm this.

10 USING THE RF-5800H TOGETHER WITH BID-1650

A Norwegian Army unit wanted to take part in the Cathode Emission Exercise in September 2004 with their newly procured Harris RF-5800H radios. A prerequisite for participation was *secure* e-mail. A way to achieve this, was to send Harris WMT messages using S5066, the BID 1650 crypto device and the internal modem (S4539) of the RF-5800H. The setup is shown in Figure 4. To achieve adaptive data rate, a crypto bypass solution for control signals was necessary, and this solution has been approved for use in military exercises by security authorities. Automatic Link Establishment (Mil-Std 188-141A) could also be used with this setup.

FFI was asked to find out whether the BID 1650 could be used together with the RF-5800H in this setup, and what we thought would be a two weeks job turned out to be a three months full time job for two persons. There were numerous problems, the three most important being:

- The clock signals from the radio were not compatible with the requirements of the BID 1650. Harris made a preliminary fix to this problem and provided us with new firmware in time for the Cathode Emission Exercise. This problem shall now have been permanently solved in the radio firmware version V 1.3.
- When operated together with the BID 1650, the S5066 protocol of the Harris WMT sometimes entered a "dead-lock" situation. This is now fixed in the WMT 6.0, but not verified by us.
- Independent of the use of the BID 1650, the S5066 introduced packet errors when run in non-ARQ mode. This is now also fixed in the WMT software, but not verified by us.

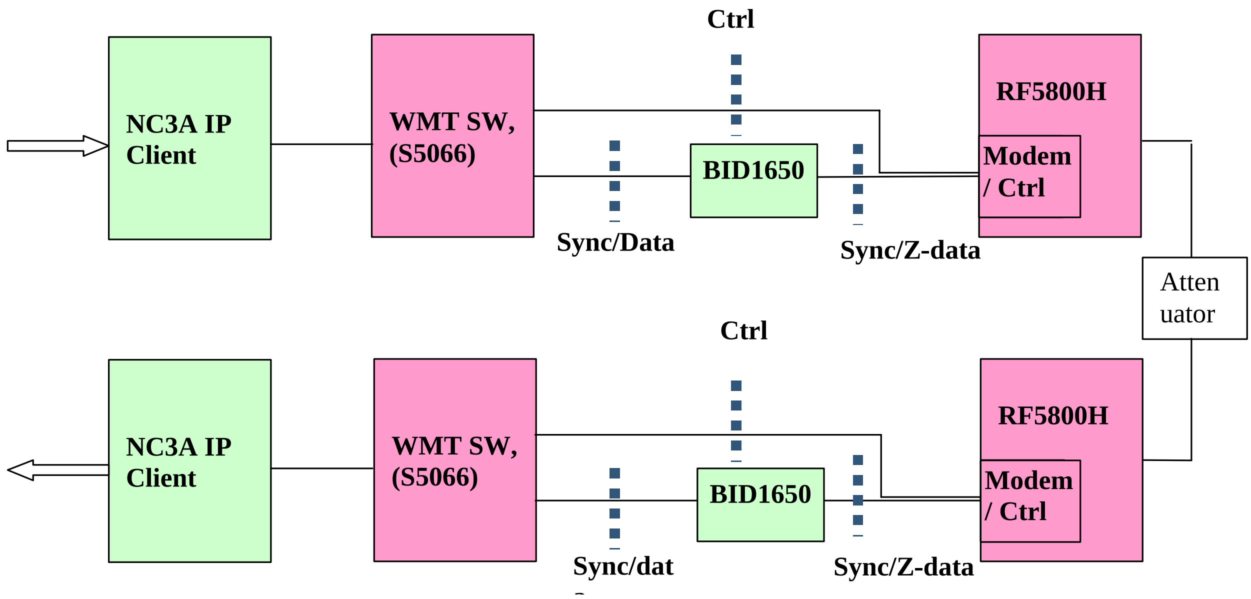


Figure 4 Set up for running S5066 with the external crypto BID 1650 and the RF-5800H

11 MMHS AS AN INTEGRATOR BETWEEN DIFFERENT BEARER SYSTEMS

The two protocol profiles of S4406, Annex C and Annex E, may provide a seemless interconnection between the strategic and tactical domain. The S4406 application may run over different networking technologies and bearer services. If IP is the networking technology of interest, and bearer services such as HF, UHF, etc are able to support IP, the S4406 application may "store and forward" messages over many hops using the underlying IP network. Static routes are defined in the various messaging servers. Since the work at SIGVAT HF also has included testing of the MMHS over the UHF radios IDM/MBITR (Thales)(5) and AN/PRC-117F (Harris)(6), we demonstrated the "store-and-forward" capabilities of the MMHS in a lab setup in November 2004. The demo setup is shown in Figure 5. The figure shows connectivity between an Army artillery battery and a Fast Patrol Boat Squadron (FPB Sq) deployed at sea and two Coastal Ranger Command Patrols (CRC) in the littoral environment. In the lab setup, the radios involved were the Multi Role Radio (VHF), the RF-5800H (2G and 3G HF) and the MBITR (UHF). Under ideal conditions in the lab, transmitting a 20 kbyte picture from the Artillery Batalion Headquarter to the Fast Patrol Boat Squadron and the Coastal Ranger Patrols took about 4-5 minutes.

The MMHS may also be used as an infrastructure for interconnection of other applications, by the use of a standardized Application Interface (API). In this way, the tactical protocol profile of Annex E may serve other applications as well.

proposed a new data link protocol for standardization, HDL+, giving higher throughput and lower latency. This protocol has also been tested. Previous work in this field has been published in [6].

The first sections of this paper describe some characteristics of the involved standards that are of importance to understand the measurements. Some implementation choices made by the vendors are also described.

2 2G HF

A 2G HF system consist of independent pieces of hardware and software that together make a fully automated radio system.

Automatic link establishment (ALE) is obtained by using Mil-Std 188-141A, in our setup implemented in software in the RF-5800H Harris radio. In 2G ALE, radios scan asynchronously, which means that the call signaling must be repeated until the receiving radio visits the actual channel where the call takes place. This gives longer link setup times than for 3G HF described in the next section. The ALE waveform uses 8-FSK modulation, and together with the coding and symbol rate chosen, the linking is not particularly robust at low signal-to-noise ratios.

When a link is established on a particular channel, data is transferred by the data link protocol defined in STANAG 5066 and appropriate waveforms defined in STANAG 4539. S5066 defines a subnetwork service interface that includes an IP service access point. IP datagrams must be included in service primitives before delivery to the data link protocol. The service primitives are handled by a separate software package, in our case software delivered from NC3A [7].

The data link protocol in S5066 provides efficient and reliable data delivery on a point-to-point link using Automatic Repeat Request (ARQ). The ARQ scheme provides feedback to the transmitter on the success of the transmissions and this information is used for adapting the data rate to the channel conditions. The data rate is adapted by “self-identifying” waveforms in S4539, informing the receiving modem on the actual data rate and interleaver setting of the current waveform. The data link protocol can also be run in broadcast mode where no feedback is provided from the receivers. This does not give a reliable delivery service and eliminates the mechanisms for adapting the data rate.

S4539 specifies a set of serial tone waveforms, all using PSK or QPSK modulation at a symbol rate of 2400 symbol/s. The waveforms provide data rates ranging from 75 bits/s to 9600 bits/s using different combinations of code rate, constellation and frame pattern. Used with an ARQ-scheme as in S5066, the throughput will be less than the unidirectional data rates mentioned here.

3 3G HF

3G HF is specified in STANAG 4538. Link setup, link maintenance, data link protocol and waveforms are all defined in the same standard, and there is a close relationship between the data link protocol and the waveforms. In the only commercially available implementation of S4538 today, from Harris Corp, all functionalities are combined in one radio.

3G HF radios are GPS time synchronized, and radios in a HF network scan the same frequencies synchronously, giving very rapid linking. The waveforms used during link setup are 8-PSK modulated and encoded with Walsh functions, making the link procedure very robust at low SNR's. S4538 defines both Fast Link Setup (FLSU) and Robust Link Setup (RLSU). Only FSLU has been implemented in the RF-5800H from Harris.

In the Harris implementation, there is a direct IP interface at the radio, supporting both Ethernet and PPP, and making the radio act as an IP router.

The data link protocol xDL is defined for a point-to-point link, and it can further be divided into two classes of protocols called HDL (High throughput Data Link) and LDL (Low latency Data Link). HDL is optimized for delivering large datagrams in medium to good channel conditions and LDL is optimized for delivering small datagrams in all channel conditions and also longer datagrams in poor channel conditions. The different performance of HDL and LDL under various channel conditions is caused by the characteristics of the different burst waveforms used. Both protocols employ ARQ and code combining for adaption of data rate to channel conditions.

The maximum gross data rate of the waveforms in S4538 (Edition 1) is 4800 bits/s. The throughput of the data link protocol using ARQ will be less. There is a finite number of forward transmission frame sizes of the data link protocol, limiting the throughput efficiency.

xDL offers a point-to-point service for both circuit and packet switched data. There is also a point-to-multipoint (multicast) service defined for circuit switched data, but not for packet switched data. Harris has however, implemented a broadcast packet service in the RF-5800H.

4 HDL+ DATA LINK PROTOCOL

The current version of S4538 (Edition 1), includes waveforms with a relatively low maximum gross data rate (4800 bits/s). In a future edition of the standard, a new data link protocol providing higher throughput has been proposed and will be incorporated. The protocol has been designed to support an efficient exchange of IP based data traffic. Harris Corp has developed and implemented this data link protocol called HDL+ [8].

The basic ideas of the protocol are to combine the high data rate waveforms of S4539 with some code combining technique, and also make the size of the forward transmission frames more flexible. This enhances the adaptivity and flexibility of the data link protocol compared to xDL in S4538, and the theoretically maximum throughput of HDL+ can be ~10 kbit/s. HDL+ gives a significant higher throughput than the current S4538 at high SNR's and benign channels. For low SNR's and difficult channels, the HDL+ protocol has no potential gain compared to the xDL protocols in S4538, and the Harris implementation resorts to xDL.

The same 3G link setup defined in S4538 is used for xDL and HDL+.

5 IMPLEMENTATION ISSUES

There are a number of radio implementation choices that influences our performance measurements.

The Automatic Channel Selection (ACS) algorithm does not affect interoperability and is therefore not standardized. However, the ranking of frequencies and the following selection of frequency to link on, has great impact on the measured throughput, particularly when channel conditions are difficult.

The data rate adaption algorithm and the corresponding selection of appropriate waveforms is also of great importance to the measured throughput. For instance, holding on to a non-robust waveform when channel conditions have deteriorated, decreases the measured throughput.

There is also an implementation trade-off between allowing for maximum throughput in one direction or traffic flow in both directions. This will also influence measured throughput, depending on measurement method.

In [6] we addressed the problem of a data source generating packet data at a high rate, higher than what can be supported by the HF link. When there is no mechanism for flow control as in our case using UDP/IP (next section), the buffer of the radio at the transmitter will overflow and subsequent packets will be discarded. However, both the Harris RF-5800H and the Thales XOmail product have implemented the Source Quench Message of the IP Control Message Protocol (ICMP), which reduces the data flow from the source. This will reduce the effect of buffer overflow, but nevertheless cause a non-optimal utilization of the link protocol. This situation will reduce the measured throughput, and in our case occurs at file sizes greater than 10 kbyte.

6 MILITARY MESSAGE HANDLING SYSTEM (MMHS)

For exploring the capabilities of a 2G and 3G HF system we have used a NATO standardized application; the Military Message Handling System (MMHS) described in STANAG 4406. In NATO, formal messaging is seen as the vehicle for secure, mission critical, operational, military applications, and e-mail systems are not. STANAG 4406 includes both a connection-oriented protocol stack suitable for strategic high data-rate networks (Annex-C) and a connectionless protocol stack suitable for tactical low data rate connections (Annex-E). Thus, a common baseline protocol solution exists so that MMHS can be used in both the strategic and tactical environments.

Over an HF link the tactical protocol stack in Annex-E obviously must be used. In addition to being connectionless which gives less overhead and avoids the large turn-around times of the link, compression is used, and there is a choice of full-duplex, half-duplex or simplex operation. It may also be used for both unicast and multicast, the latter providing efficient use of radio resources. There are also procedures for handling recipients under Emission Control (EMCON).

Since the Annex-E protocol profile uses a connectionless transport service, there is no inherent transfer reliability. This is compensated for by the introduction of the P-Mul sublayer. The P-Mul protocol is defined by the military standard ACP 142 [ref]. This sublayer has functionality for both unicasting and multicasting of messages. It splits the message into smaller Protocol Data Units (PDU’s), attaches a checksum, numbers the PDU’s and handles retransmissions based on a selective repeat procedure. Since the P-Mul protocol supports retransmissions of lost packets, the bearer service does not need to be reliable (i.e. broadcast). However, both the 2G and 3G HF systems were run in ARQ-mode in our tests, providing a reliable service to the application.

A connectionless WAP transport protocol called the Wireless Datagram Protocol (WDP) is specified in Annex-E. This protocol is more flexible than the UDP protocol in that it does not mandate the use of IP. If IP is used however, the WDP protocol becomes UDP. In our tests where the HF radio provides an IP service, Annex-E uses the UDP protocol, and the traffic flow is essentially unidirectional over the HF circuit.

7 MEASUREMENTS

The performance of the HF protocols was evaluated by testing in controlled lab environments as well as by on-air measurements. The lab testing was limited to AWGN channels. All testing reported in this paper is performed with IP traffic generated according to STANAG 4406 Annex E implemented in the XOmail product from Thales.

The practical test-setup for 2G testing and 3G/HDL+ testing was slightly different, reflecting only differences in the practical implementation of the two protocols as described above. The test setups are shown in Figure 1 for the 3G/HDL+ testing (left) and 2G testing (right).

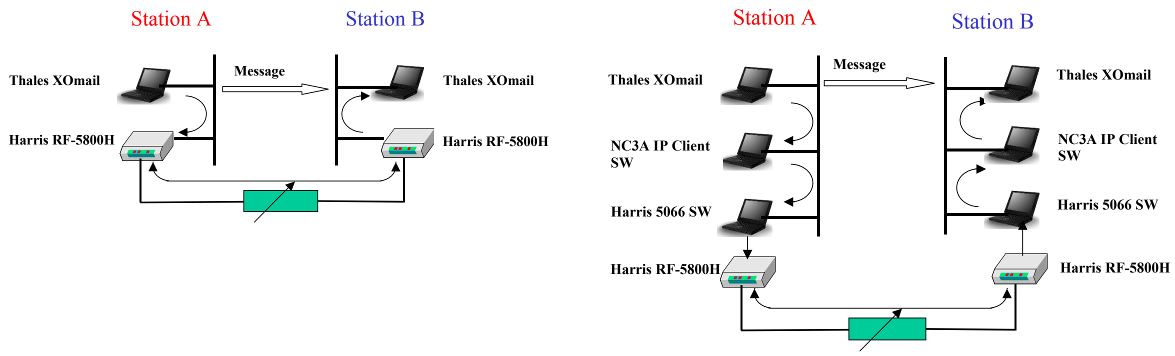


Figure 1 Test setup for MMHS over a 3G HF system (left) and a 2G system (right)

The measurements were made by observing the transfer times of XOmail messages when repeatedly transmitting compressed messages with a known compressed message length L. Thereby, an estimate of the mean transfer time for all the repetitions T_{mean} could be calculated. The instantaneous throughput of the message repetition i is defined as $G_i = L/T_i$, where T_i is the transfer time of the specific repetition. Likewise, the mean throughput for all repetitions is defined as $G_{mean} = L/T_{mean}$. The number of repetitions of a measurement series was normally 10, except in situations with very high transfer times or when particular conditions prevailed. Each new transmitted message was released only after the previous ALE session was fully terminated, necessitating a new automatic link establishment. Hence ALE setup times are included in the measured transfer times and in the throughput calculations. A pool of 10 different frequencies defined the HF net.

From the definitions above, it is noted that the throughput figures in this paper relate to the application throughput, i.e. the average number of compressed application data bits transferred per seconds. The throughput of the HF link will be higher, because of the overhead introduced by the XOmail application and the overhead of the UDP/IP packets. For the configuration of XOmail used during the measurements, the relationship between the throughput of the HF link and the application throughput can be approximately expressed as:

$$G_{link} \approx G_{appl}*(1{,}0887 + 700/L) \qquad (1)$$

where G_{link} and G_{appl} is the throughput at the link level and the throughput at the application (message) level respectively, and L is the length of a compressed message.

The measured transfer times depend upon the standardized protocols as well as radio implementation choices, as mentioned earlier. In addition, the transfer times are impacted also by the traffic characteristics and the protocols of the application, such as the rate of arrival of IP packets at the radio and the size of the IP packets. The latter parameters were fixed within a suitable range and kept constant during all the measurements.

7.1 MEASUREMENTS AND COMPARISONS IN THE LAB

The protocols were explored in the laboratory using the block schematics of Figure 1, with the additional insertion of additive white Gaussian noise at a controlled level at the inputs of each radio. The measurements consisted of two parts. First, the protocols were tested under "ideal" channel conditions with different message lengths. During these measurements the SNR was set to about 37 dB, making use of the highest speed waveforms technically feasible. All 10 frequencies were operated with the same SNR, thus eliminating the importance of the channel selection algorithms.

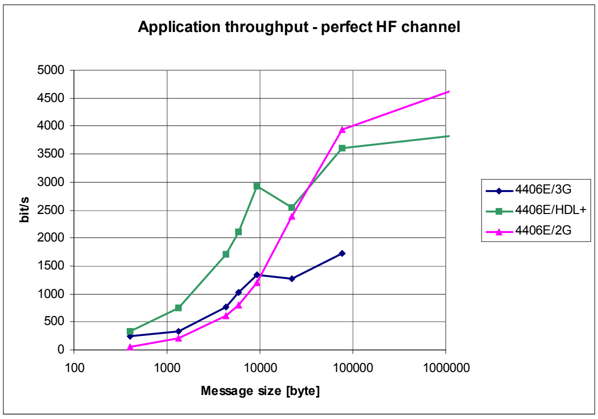
Secondly, the throughput was measured as a function of the SNR, keeping the message length constant. The SNR was identical at both ends of the link.

Figure 2 (left) shows how the average throughput on an "ideal" channel varies with the message length for the three different HF protocols. The 3G protocol offers less throughput than 2G for large message sizes. This is because the 3G waveforms offer a lower maximum data rate than the waveforms of 2G. The HDL+ protocol performance is superior to that of 3G for all message lengths. It is noted that a slight reduction in the application throughput performance for the HDL+ and the 3G protocols occurs for messages larger than 10 kbyte. This is a consequence of buffer overflow in the radio and the impact of the Source Quench message on the packet flow from the XOmail application. The effect is not visible for the 2G protocols because the traffic from XOmail enters into the NC3A IP client software (Figure 1). The latter has a large enough buffer capacity to avoid overflow for the message sizes used in these tests.

The reason for the poor throughput performance of the 2G for low to moderate message length is the slow automatic link establishment of the 2G system. The throughput of the 2G protocol will improve significantly for these message lengths in the absence of ALE.

Figure 2 (right) also shows the measured throughput performance of the protocols as a function of the SNR on an AWGN channel. The compressed message length is 9.3 kbyte. For positive SNRs the HDL+ protocol gives a superior performance, justifying a revision of the STANAG 4538. However, for low SNRs the performance of the HDL+ and the 3G protocols was similar. This is according to expectations, since the two protocols use the same waveforms for low SNRs. The long linking time of the ALE protocol in the 2G HF system prevents its throughput performance to approach that of the 3G protocol at positive SNRs, and its low robustness prevents any message transfer at all for the lowest SNRs.

The link level throughput will be about 16% higher than those shown in Figure 2, as given by equation (1). Even at SNRs approaching 30 dB the link throughput of the lab tests of HDL+ is less than half the throughput figures reported in [8] for a 5 kbyte message. This is not the case for the 3G results from [8], which is in better accordance with the results of Figure 2. The reasons for this discrepancy for the HDL+ protocol are not fully understood, however, it might be related to implementation effects of the HDL+ protocol and to the arrival rate of IP packets from the message source not satisfying the conditions for maximum throughput.



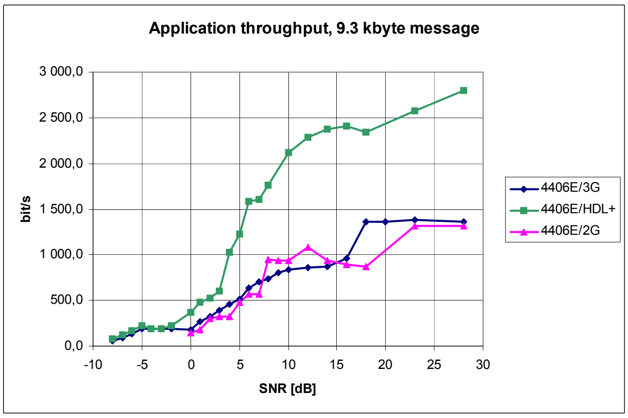


Figure 2 *Comparison of throughput versus message size (left) and comparison of throughput versus SNR for a 9 kbyte message (right) for 2G, 3G HF and HDL+*

7.2 MEASUREMENTS AND COMPARISONS OVER-THE-AIR

The comparative testing of the three protocols proceeded by measuring the throughput performance of a HF link between Lillehammer and Kjeller in southern Norway. This link is believed to be fairly representative of a tactical NVIS link between vehicular equipments; the distance being approximately 140 km and the transmit power being 125 W.

Measurements were conducted in March/April 2004 mostly under benign conditions, the local geomagnetic K index was never above 3 for the data shown in this paper. The noise level at Kjeller was particularly high during daytime causing the SNR to be 10-15 dB lower than at Lillehammer. Lilehammer was therefore chosen as receive site for all the measurements.

The same pool of 10 frequencies was used during all measurements. In order to compare the protocol performance, the protocols were tested in sequence during a sub-period as illustrated in Figure 3. Before the measurements of the message transfer times commence in each protocol measurement interval, there is a configuration phase. For each protocol, this phase also contained channel soundings, so that the ACS algorithms can take advantage of up-to-date information on channel quality scores at the start of the measurement phase of each protocol.

After a number of independent message transfers with a given HF protocol, the mean throughput was calculated and used as the throughput estimate at the universal time corresponding to the middle of the observation interval. Also the minimum and the maximum instantaneous throughput values in the measurement interval were calculated.

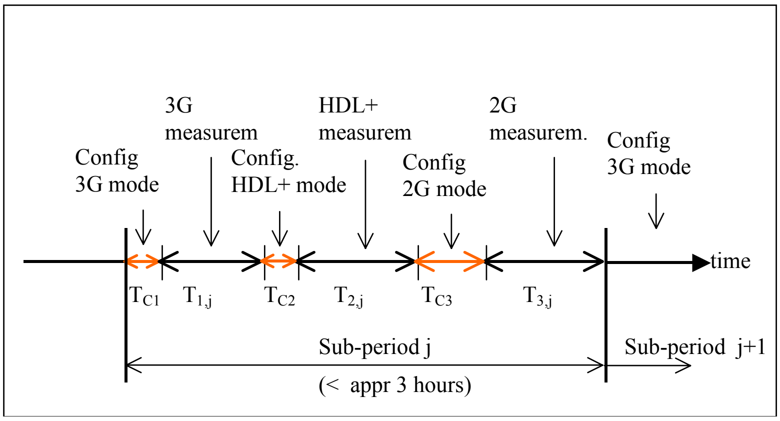


Figure 3 Test schedule of different protocols over-the-air

A message length of 9,3 kbyte has been used during most of the testing, and normally the number of repetitions of a message transfer was set to 10, resulting in a measurement interval per protocol of between 20 and 60 minutes. The variation of the message transfer times, and consequently the instantaneous throughput value, during each measurement interval could in some cases be significant. Not only the channel conditions seemed to contribute to this variation. Sometimes the ACS system would pick an unfortunate frequency, the effect of which was a sharp increase in the transfer time. This was more noticeable for the HDL+ measurements than for the measurements of the 3G and 2G system.

Figure 4 illustrates short-term variability of the HDL+ measurements by showing the average transfer time for each interval along with the maximum and the minimum transfer times measured during the 10 repetitions.

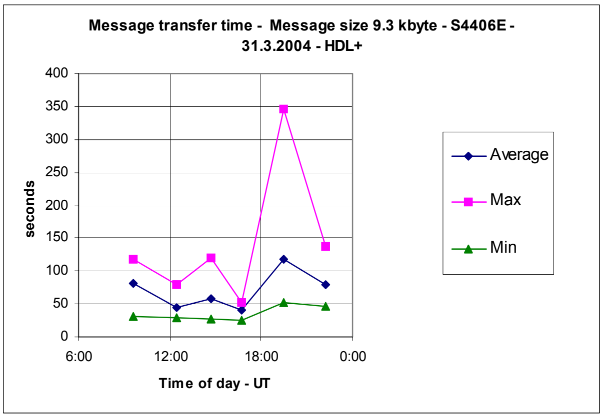
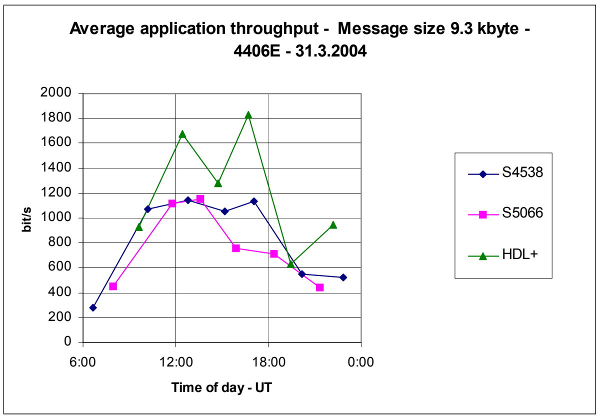


Figure 4 Short-term variability of the message transfer time of the HDL+ protocol

Figure 5 compares the average throughput for each measurement interval for the three protocols for the transfer of a 9,3 kbyte message (left) and a 22 kbyte message (right).

The results of the over-the-air testing confirm the impression that the HDL+ protocol offers an overall performance improvement for the transfer of short to medium length messages. However, it is noticed that under good day-time conditions with SNRs above 20 dB, the measured average throughput for the HDL+ remained well below the simulated throughput for a 5 kbyte message on an ITU Poor HF channel [8].



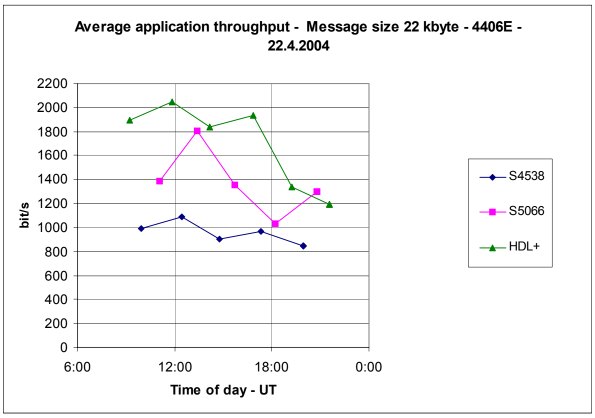


Figure 5 *Comparison of application throughput using the different HF protocols. 9 kbyte message (left) and 22 kbyte message (right)*

The difference between the measured performance between the HDL+ and 2G is primarily caused by to the less efficient linking protocols of the 2G.

It is expected that the message lengths in the tactical network in many cases will be much lower than 9 kbyte. Figure 6 compares a set of measured application throughput values for the HF protocols for message sizes of 403 byte, 1,3 kbyte and 9,3 kbyte. Each bar represents the average of 10 measurements. As expected, the throughput degrades rapidly as the message size is reduced, illustrating the fact that the HF protocols need to operate on large messages in order to achieve good throughput values.

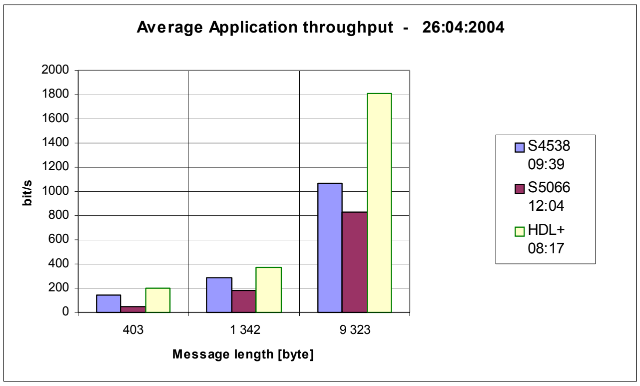


Figure 6 *Comparison of application throughput for various file sizes and HF protocols*

8 CONCLUSIONS

Testing a 2G and 3G HF system as part of an IP network using traffic from a STANAG 4406 Annex E message server has shown that the throughput of such a system can be lower than expected from knowledge of the optimum throughput capacity of the HF data link. This is related to the interaction between the offered load from the application and the HF data link protocols.

The linking used by the 2G HF system deteriorates the performance compared to the 3G system both in efficiency and robustness. This is particularly evident for small file sizes were the transmission time is short. The throughput of HDL+ is superior to that of 2G and 3G HF at positive SNR's. However, for larger file sizes (>22 kbyte) the performance of 2G approaches that of HDL+. At negative SNR's, 3G still provides communications whereas 2G fails to link. Implementation choices, such as ACS and the data rate adaption algorithm, have a great impact on the measured throughput.

ACKNOWLEDGEMENT

Thanks to Harris Corporation for technical support of this work.

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[5] NATO Standardization Agreement (STANAG) 4538, Edition 1, Technical Standards for an Automatic Radio Control System (ARCS) for HF Communications Links

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D APPENDIX : NATO MILITARY MESSAGING IN THE TACTICAL DOMAIN – PERFORMANCE ISSUES OF AN HF CHANNEL

NATO Military Messaging in the Tactical Domain –performance issues of an HF channel

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SUMMARY

NATO STANAG 4406 for Military Message Handling Systems (MMHS) may be used for direct information exchange between the high data rate strategic domain and the low data rate tactical domain by using the tactical protocol profile specified in Annex E. This paper explores the performance of the MMHS application over NATO standardized HF radio systems using both unicast and multicast IP services. A comparison of performance is made with a dedicated HF messaging application, and advantages/disadvantages by using the IP based application are pointed out. MMHS Annex E over HF systems is a viable solution, providing application throughputs up to a few kilobits per second. There are however, optimisation issues at different levels of the protocol stack, and we have seen that implementation choices and parameter settings have great impact on the overall performance of the system.

1.0 INTRODUCTION

Interoperability between communications equipment used by military forces from different countries is very important in todays battlefields. During the last ten years NATO has produced a number of standards (STANAGs) for military information systems, ranging from applications to bearer services such as HF communications. Using standardized protocols at all levels of the protocol stack provides interoperability and flexibility. IP will be the integrating networking technology in future military communications network, and many nations are planning to use IP as a platform for their communication systems in both the strategic and tactical domains. This will provide increased interoperability between strategic and tactical systems. However, there may be challenges when the TCP/IP protocol suite is used over tactical communication systems with variable quality and data rate. Traditionally for tactical communication systems, applications have been uniquely tailored to the bearer service. This provides efficient utilization of the channel capacity, but at the cost of flexibility and re-use of the same applications.

This paper describes the exploration in the lab and over-the-air of a NATO standardized application; the Military Message Handling System (MMHS) specified in STANAG 4406, used together with NATO standardized HF communication systems specified in STANAG 4538 (3G HF) and STANAG 5066 (2G HF). A new HF datalink protocol (HDL+) proposed for standardisation, is also included in the evaluation. STANAG 4406 for MMHS includes both a strategic and a tactical protocol profile, which may be used for exchanging information between the high data rate strategic domains and the low data rate tactical domain. We discuss the use of IP as an integrator between the MMHS application and the HF bearer services. The MMHS may also be used as an integrator between tactical bearer systems such as HF/VHF/UHF/WLAN.

In NATO Network Enabled Capabilities (NNEC) seamless interconnection of systems and networks is an

V. Jodalen, A. Eggen, B. Solberg, O. Grønnerud (2005) NATO Military Messaging in the Tactical Domain - performance issues of an HF channel. In *Military Communications* (pp. 11-1 – 11-16). Meeting Proceedings RTO-MP-IST-054, paper 11. Neuilly-sur-Seine, France: RTO. Available from:

important factor. In the migration process towards NNEC, we believe the MMHS based on STANAG 4406 may be used as an integrator between strategic and tactical systems because most NATO nations (including the NATO organization) recently have procured systems in accordance with this standard.

2.0 NATO MILITARY MESSAGING

A Formal Military Message is different from an interpersonal message in that it is a message sent on behalf of an organization, and that it establishes a legal commitment on the sending and receiving organization under military law. Examples of formal messages are military orders.

Formal Military Messages are handled by Military Message Handling Systems (MMHSs). An MMHS takes responsibility for the delivery, formal audit, archiving, numbering, release, emission, security and distribution of received formal messages. In NATO, the formal messaging service is seen as the vehicle for secure, mission critical, operational, military applications (e-mail systems are not). STANAG 4406 Ed.1[1] [1] is the only agreed standard to achieve interoperability between the formal messaging systems of NATO nations. Systems compatible with the S4406 standard have been and are being implemented widely by the NATO nations and by the NATO organization.

2.1 Military Messaging in the tactical domain

The original connection oriented protocol stack defined in S4406 Annex C (and ACP 123 [2]) was developed for strategic high data rate networks, and is not suitable for channels with low data rate. A protocol solution defined in Annex E of S4406 has therefore been developed for *tactical* communications. With the inclusion of this protocol profile in S4406, a common baseline protocol solution exists that opens for a seamless interconnection of MMHS between the strategic (fixed) and tactical (mobile) environments. One messaging system may therefore be used to communicate with all national forces, the NATO organization and the NATO allies. In Figure 1 the MTA (Message Transfer Agent) may be used as a gateway between the strategic and tactical domain if the dual stack is implemented.

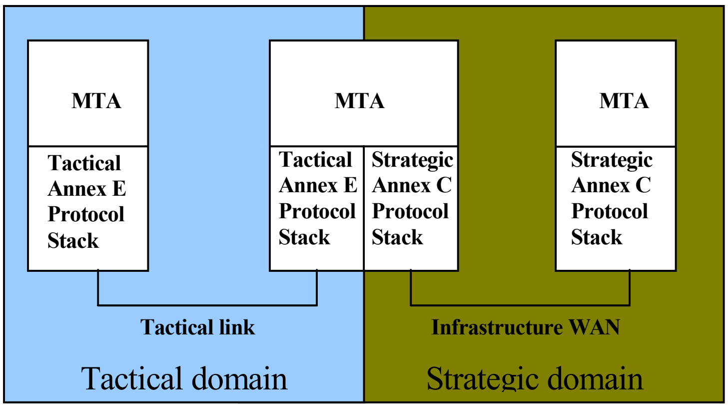

Figure 1: Seamless interconnection of MMHS between the strategic and tactical domain

To take account of the characteristics of a tactical radio link, the Annex E protocol profile has adopted the following:

[1] STANAG 4406 Edition 2 is out for NATO ratification at the time of writing.

- A connectionless protocol stack, which gives less overhead and reduces the effect of large turn-around times of the link
- A choice of full-duplex, half-duplex or simplex (broadcast) operation
- Compression to reduce the amount of data transmitted
- It may be used for both Unicast and Multicast, the latter providing efficient use of radio resources
- Procedures for handling EMCON recipients

The protocol profile in Annex E is divided into an application layer and a transport layer on top of potential bearer systems. Among several sub-layers, the P-Mul protocol (ACP-142 [3]) is introduced to compensate for the lack of transfer reliability of the connectionless protocol stack. It splits the message into smaller Protocol Data Units (PDU's), attaches a checksum, numbers the PDU's and handles retransmissions based on a selective repeat procedure. The P-Mul sub-layer has also functionality for both multicasting and unicasting of messages. The transport layer of Annex E uses a connectionless WAP protocol called the Wireless Datagram Protocol (WDP). This protocol is more flexible than the UDP protocol in that it does not mandate the use of IP. However, for IP networks the WDP protocol becomes UDP. In our test where the HF radio provides an IP service, Annex E uses the UDP protocol.

These features of Annex E increase the messaging throughput substantially for tactical communication channels with low data rate compared to the connection oriented Annex C protocols. We have used the Thales XOmail implementation of S4406 in our tests, including both the tactical (Annex E) and strategical (Annex C) protocol profiles.

3.0 TACTICAL RADIO COMMUNICATIONS

Tactical communications are used by highly mobile units not being able to utilize a fixed communications infrastructure. Typical tactical units requiring long range tactical communications are: Naval vessels, aircrafts, land mobiles and special forces carrying manpack radios. The characteristics of long range tactical radio communications in general are:

- Only low to moderate data rate is supported (typically < 10 kbit/s)
- Variable data rate depending on time, location and other users of the radio spectrum
- Unreliable connections; high bit error rates, frequent link terminations, unreachable nodes, equipment failure
- Half duplex or simplex channels, giving large turn-around times
- Different types of radio equipment
- Emission Control (radio silence) conditions are often required

3.1 NATO HF Communications

The above characteristics apply to HF communications in particular, since HF propagates via reflecting layers of the ionosphere that supports a very limited data rate. Under very favourable conditions, a maximum of 9.6 kbit/s user data rate can be achieved in a 3 kHz channel. However, the data rate is normally much lower due to absorption of the signal, manmade noise and interference. Also, rapid time fading and excessive multipath impose a reduced data rate. HF radio systems normally operate in half duplex mode. The advantage of HF communications is extraordinary radio coverage well beyond line-of-sight.

NATO has developed a family of standards at the physical and data link layer within the "HF House" concept. The HF House covers what is called 2G HF technology and 3G HF technology, both of which contain descriptions on *automated* procedures at the link level, appropriate waveforms to be used at the physical level and how the HF subnetwork can interface a data network. Our tests described in this paper have included both 2G and 3G HF technology and also a new data link protocol (HDL+) that will be standardized in the near future. The most important characteristics of the respective HF technologies are described in the following sections.

3.1.1 2G HF

A common operational configuration of a 2G HF system is based on the following set of HF standards: Mil-Std 188 141A [4], STANAG 5066[5], and STANAG 4539 [6]. Mil-Std 188 141A provides automatic link establishment (ALE) in a net of HF radios scanning asynchronously. The link set up may take some time depending on the number of frequencies in the scan set. The waveform used for linking is not particularly robust at low signal-to-noise ratios. When a link is established, the data link protocol defined in S5066 provides efficient and reliable data delivery on a point-to-point link using Automatic Repeat Request (ARQ) and appropriate waveforms defined in S4539. The ARQ scheme is used for adapting the data rate to the channel conditions. The gross data rates provided by the waveforms in S4539 range from 75 bit/s to 9.6 kbit/s. The data link protocol can also be run in broadcast mode where no feedback is provided from the receivers. This does not give a reliable delivery service and eliminates the mechanisms for adapting the data rate.

S5066 defines a subnetwork service interface that consists of a number of service access points (SAP's), including a SAP for IP. IP datagrams must be included in service primitives before delivery over the SAP to the data link protocol. The conversion between IP datagrams and S5066 service primitives is handled by a separate software package, in our case the IP Client software delivered from NC3A [7]. Other SAP's defined in S5066 provide an efficient interface to other applications, for instance HF mail applications such as HMTP and CFTP, without any intervening transport and networking protocols such as UDP/TCP/IP.

For the standards defined above we used the Harris implementation in their RF-5800H radio product and the Harris WMT S5066 software package.

3.1.2 3G HF

For 3G HF, STANAG 4538 [8] includes all the functionalities such as link setup, data link protocol and waveforms. The link setup defined in S4538 is based on all radios scanning a set of frequencies synchronously. The fast link setup (FSLU) used in our tests gives very rapid linking. The waveforms used for link setup are also very robust, enabling linking at negative signal-to-noise ratios. The data link protocol xDL is defined for a point-to-point link and gives an adaptive and reliable data delivery using ARQ and code combining. It is further divided into two classes of protocols called HDL (High throughput Data Link) and LDL (Low latency Data Link). HDL is optimised for delivering large datagrams in medium to good channel conditions and LDL is optimised for delivering small datagrams in all channel conditions and also longer datagrams in poor channel conditions. HDL and LDL use different waveforms with different robustness. The maximum gross data rate for xDL is limited to 4.8 kbit/s, which limits the throughput performance compared to 2G HF. All of the described functionalities of S4538 are implement in the RF-5800H from Harris used in our tests.

S4538 does not currently define a multicast/broadcast mode for packet data. However, the Harris RF-5800H radio provides a proprietary broadcast packet service where the data rate is fixed.

No subnetwork service interface is currently described in S4538. In the Harris implementation, there is a direct IP interface at the radio, supporting both Ethernet and PPP, and making the radio act as an IP router.

Applications using IP services may therefore connect directly to the radio.

3.1.3 The new data link protocol HDL+

A new data link protocol has been proposed by Harris to become a part of S4538 in the future. HDL+ is a point-to-point protocol and will to a large extent replace HDL, providing higher throughput and lower latency on good HF channels. The protocol has been designed to remove the data rate limitation of S4538 and to support an efficient exchange of IP based data traffic. The same efficient link setup is used for HDL+ as for 3G HF. The data link protocol combines the high data rate waveforms of S4539 with some code combining technique, and gives an adaptive data link protocol capable of error free delivery up to 10 kbit/s in a 3 kHz channel [9]. For poor channels the HDL+ has no potential gain compared to the LDL protocol in S4538, and the Harris implementation resorts to LDL. The same IP interface as for 3G applies to the HDL+ protocol.

3.2 IP over HF

The communications scenario we discuss in most of this paper is described in Figure 2. An HF link is used to connect the IP networks A and B. Two data terminals are hosting a S4406 Message Transfer Agent for provision of a seamless MMHS service to the mobile platform. The nodes HF A and HF B each comprise the HF radio/modem functionality, the HF link protocols, an optional link crypto functionality and finally an IP routing functionality.

Compared to most other links used in an IP network, the throughput of a typical HF link will be very low and variable, and the latency will be very high. In order to take advantage of the IP service offered by the HF radio link, the protocols above the network layer must be able to tolerate the high latency imposed by the HF link protocols. TCP is not particularly suitable for use over HF because of the variable capacity of HF requiring conservative timer settings and because the cost of reversing the channel at HF is rather high. In most cases the HF link will inevitably represent a bottleneck in the IP network with a great impact on the quality of service being offered to the user.

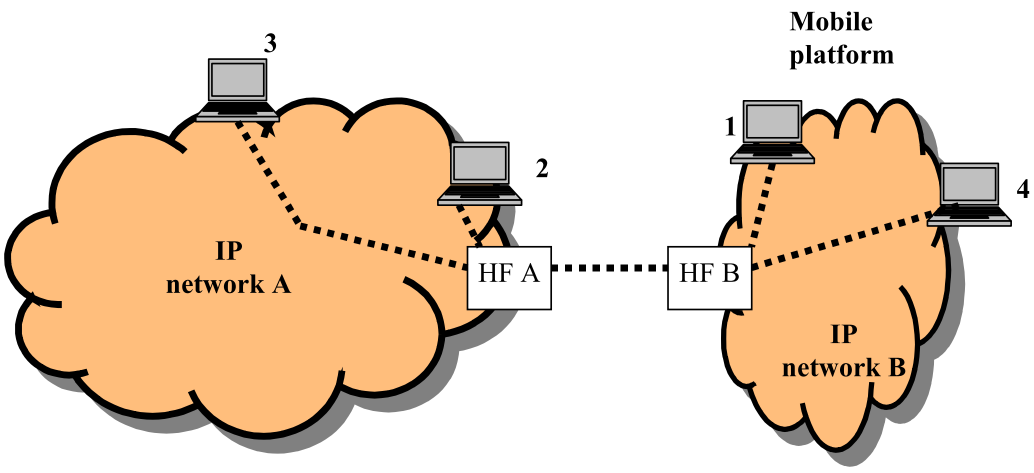

Figure 2: Model of IP networks connected by HF

4.0 PERFORMANCE OF THE NATO MESSAGING APPLICATION OVER HF LINKS

The aim of this study has been to explore the efficiency of the message transfer of the MMHS by using a transparent IP service over the different HF technologies and to understand the interactions between the protocols. Focus has been on efficiency over a point-to-point link, and measurements have been conducted in both the laboratory and over-the-air. Earlier published results can be found in [10], [11] and [12]. We have also addressed the Multicast properties of S4406 Annex E utilizing the Harris proprietary Broadcast protocol of RF-5800H. Laboratory measurements illustrate a few points about the efficiency of Multicasting over HF.

4.1 Recapitulation of earlier published results

Our first investigations were conducted in the lab under controlled channel conditions. The test setup was similar to the setup shown in Figure 3, except that the radios were connected with attenuators, and there was no need for a modem to control one of the radios. White Gaussian noise was inserted at a controlled level at the inputs of each radio, but no fading model was used. A frequency set consisting of ten frequencies has been used throughout the tests.

Figure 3 shows the test setup for the over-the-air tests that were conducted between Lillehammer and FFI at Kjeller, a 140 km path in southern Norway. A modem over the telephone network enabled us to control and monitor the message reception at the remote site, and transfer times were recorded. The power transmitted was 125 W and the antennas were broadband dipoles.

Thales XOmail (S4406) was located at the PC's together with the WMT S5066 software. For the 2G tests, a second PC hosted the IP Client software on each side.

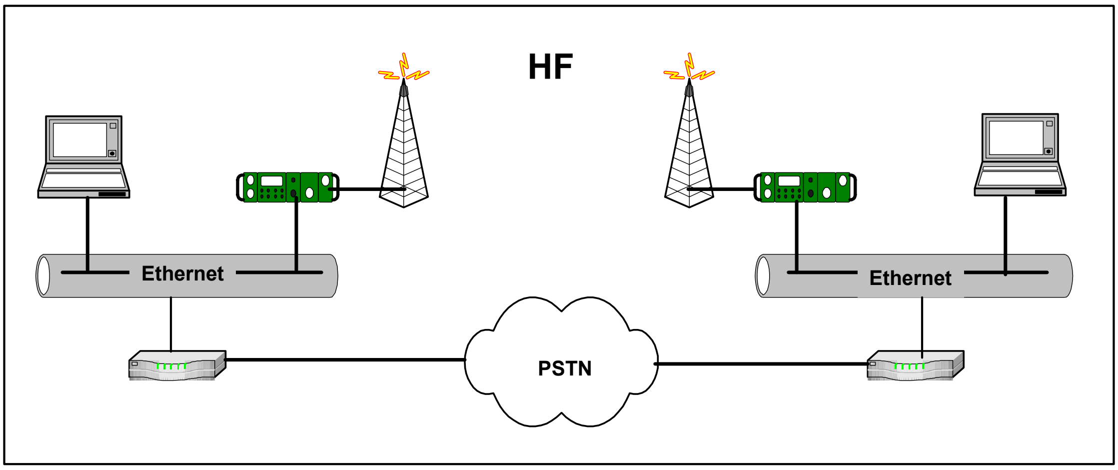

Figure 3: Over-the-air test setup

Compressed messages were transferred between the messaging application at each site, and the transfer times were recorded. The *application level throughput* was calculated as the compressed message size divided by the delivery time. Since the message is delivered before all the protocol layers have been released, the throughput calculations are slightly optimistic, in particular for short messages. Each measurement was repeated around 10 times and averaged. ALE/FLSU are included in the measured transfer times and in the throughput calculations.

4.1.1 Throughput

Comparing the througput performance on a "perfect" channel of the Annex C (strategic) and Annex E (tactical) protocol profile over S4538 (3G HF) shows that Annex E improves the throughput by a factor of six for a 400 byte file and by a factor of 2 for a 75 kbyte file. The improvement factor increases as the HF channel deteriorates, so that on a typical HF channel, the improvement factor will be higher than the figures mentioned here. In the following, only the Annex E protocol profile has been tested further since it outperforms the Annex C profile over an HF link.

We observed that transfer times (and therefore throughput) were affected not only by the protocols in use and the channel conditions. Also implementation choices made by the equipment vendors and configuration parameters selected by the user, contribute to the transfer times. For instance, the HF standards define a number of different waveforms, but the choice when to use the different waveforms is up to the vendor. Also frequency selection algorithms, buffer size and buffer handling are implementation dependant. Moreover, the transfer times depend on configurable parameters of the application such as PDU size and packet rate. Consequently, the throughput measured is only indicative of what can be obtained, and does not serve as a definite upper limit.

Our next observation focuses on the different HF link protocols (2G, 3G and HDL+) as the carriers of S4406 Annex E message traffic. We measured application throughput for various file sizes ranging from 400 bytes to 75 kbyte over an error-free channel. The results are shown in the leftmost panel of Figure 4. For message sizes below 10-20 kbyte, the HDL+ protocol gives twice as much throughput as the 3G and the 2G protocol. The 2G protocol suffers from in-efficient linking using Mil-Std 188 141A, and the 3G protocol suffers from low data rate waveforms. For larger message sizes (>20 kbyte) the effect of in-efficient linking for 2G is reduced and 2G performs at the same level as HDL+, but 3G still suffers from low rate waveforms. We will come back to the dip in throughput around message sizes of 20 kbyte for HDL+/3G in the next section. The rightmost panel of Figure 4 shows the application throughput versus signal-to-noise ratio on the channel for a fixed message size; 9.3 kbyte. At positive SNR's the HDL+ protocol provides the best performance whereas HDL+ and 3G provides similar results at negative SNR's. The 2G link establishment is less robust than 3G/HDL+, and linking is not achieved at negative SNR's.

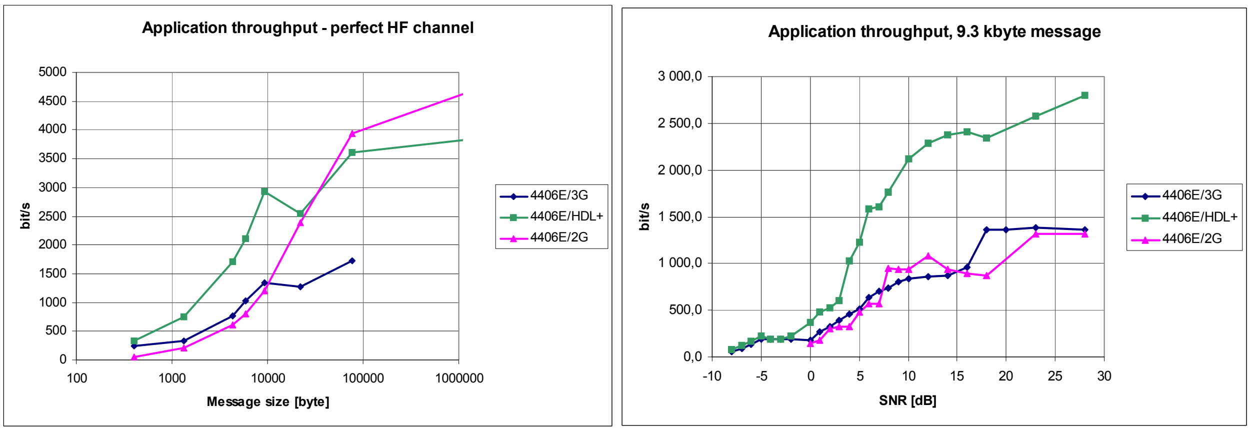

Figure 4: Comparison of throughput vs message size (left) and comparison of throughput vs SNR for a 9.3 kbyte message (right)

To compare the performance of the different HF protocols as bearers for S4406 traffic *over-the-air*, the protocols were tested in sequence but within a maximum time period of three hours. At the start of measurements for each protocol, channel quality scores in the radios were updated by channel soundings allowing an optimum frequency selection. Measurements were conducted in March/April 2004 under benign conditions, the local geomagnetic K index was never above 3 for the data shown in this paper.

However, the diurnal variability of the HF channel was quite noticeable. Figure 5 shows averaged application throughput vs time of day for a message size of 9.3 kbyte (left) and 22 kbyte (right).

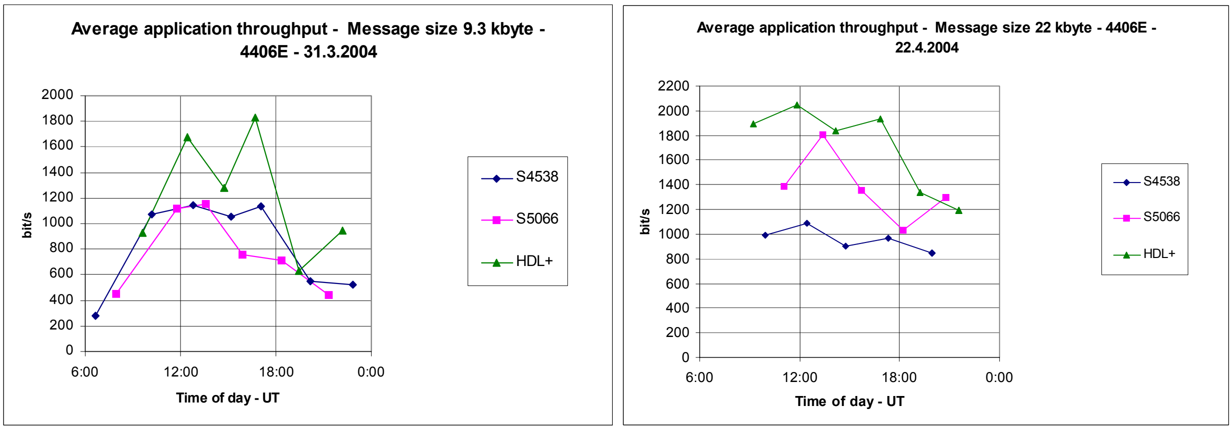

Figure 5: Comparison of throughput over-the-air vs time of day for a 9.3 kbyte message (left) and a 22 kbyte message (right)

The following conclusions can be drawn from the over-the-air tests of S4406 over the various HF protocols:

- Under good day time conditions (SNR > 20 dB) the measured average throughput for HDL+ remained well below the simulated throughput of 4500 bits/s for a 5 kbyte message on an ITU poor channel referred in [9]. Our results include the effect of non-optimum offered load from an application and realistic channel conditions which may be worse than the ITU poor channel.
- The variation of the message transfer times (and therefore throughput) when transmitting 10 consecutive messages for each HF protocol, is significant.
- The automatic channel selection algorithm of the radio is very important for achieving high throughput.
- The difference between the measured performance of the HDL+ protocol and 2G is primarily caused by the less efficient linking protocol of the 2G, and the effect of this is lower for larger message sizes.

4.1.2 Congestion control aspects

Referring to Figure 2, IP packets may arrive at the HF transmit node at a higher rate than the node is able to support, and hence, packets will accumulate in buffers at the HF node. With respect to the throughput of the HF link this is desirable, because the HF protocol efficiency improves with full radio buffers. However, since neither P-Mul nor UDP has mechanisms for network congestion control, buffers in the HF transmit node will tend to overflow, and packets will be discarded for long messages. The discarded packets will be retransmitted by P-Mul, but this effect may severely deteriorate the overall performance of the Annex E protocol stack.

The present XOmail implementation of ACP 142 P-Mul protocol and the IP service of the RF-5800H come around this problem by introducing a "local" congestion control mechanism, which makes use of the IETF standard "IP Control Message Protocol" (ICMP) (13). When the buffer of the HF transmit node overflows, an ICMP Source Quench message is generated and sent to the originating end terminal. This message will instantaneously stop the packet flow from P-Mul, thereby minimizing the influence of the buffer overflow. A timer will start the packet transmission again.

The buffer size of the RF-5800H in our 3G and HDL+ setups is about 10 kbyte. For message sizes exceeding the buffer size, a packet is discarded before the Source Quench is effectuated with a following reduction in throughput as seen in Figure 4 (left). The buffer size of the IP Client of the 2G HF subnetwork (software on a PC) is much higher, and no packets are discarded in the 2G measurements.

Although not perfect, by using the Source Quench mechanism for congestion control a reasonably high throughput capability will be achieved also when transferring long messages. However, there are unresolved issues regarding the use of the Source Quench mechanism. A new version of ACP 142 is under development by NATO and the CCEB, which will include functionality for end-to-end congestion control (see section 6.1).

4.2 Multicast

The broadcasting nature of radio nets can be utilized to offer an IP multicast service. This implies that IP data packets are broadcasted over the radio net and delivered to those addresses defined by the IP multicast address. In its simplest and most common form a multicast link service is based on broadcasting without link acknowledgements/retransmissions, and hence provides a less reliable service than unicasting. Multicasting may provide a potentially bandwidth efficient transfer capability, especially when there are many recipients of a message in the same radio network.

2G HF (S5066) offers a broadcast packet service. The 3G HF (S4538) in its present version does not. However, the implementation of S4538 from Harris that we are using in our tests, extends the present S4538 to provide a simple IP broadcasting service, on which a limited IP multicast service can be based. One of the key features of the STANAG 4406 Annex E is the multicast ability of the P-Mul protocol. We have done some introductionary testing to investigate how well this protocol will work on an HF network with S4538 extended with the IP broadcast protocol.

A multicast message transfer from A to three recipient nodes B – D has the following phases:

1. Transfer of the P-Mul Control PDU and the P-Mul traffic PDUs from A. Radio A sets up a channel on a suitable broadcast frequency and sends these PDUs by IP broadcasting at a fixed data rate.
2. Transfer of the P-Mul ACK/NACK control packets from each of the nodes B – D by using the S4538 unicast service.
3. Unless all the nodes have given a positive acknowledgement, P-Mul at node A will retransmit missing PDUs, and the nodes B – D will update their acknowledgement status. This repeats until all the nodes have received all PDUs from A.
4. When the P-Mul entity of node A has received acknowledgements from all the addressees, it will send an end-of-message (EOM) by IP broadcast, terminating the message transfer.

Thus, all P-Mul packets transmitted from node A use the IP multicast service, whilst the individual P-Mul ACK/NACK packets in the reverse direction use the unicast service. While the latter is a robust service with adaptable data rates and link acknowledgements, the former is a fixed data rate service without link acknowledgements. Hence the probability of delivery of a multicast message is strongly dependent on the fixed data rate selected for the channel. Unless a relatively low data rate is chosen for the broadcast channel, the IP multicast service will not be very effective in delivering messages to addressees that are operating on HF channels with low SNRs. For example, as a guideline, by using a data rate of 600 bit/s, HF channels with an SNR of a few dB's are required for acceptable delivery of multicast traffic. Increasing the rate to 4 800 bit/s increases the SNR requirements by about 10 dB.

Figure 6 shows a picture illustrating the difference in channel activity between the IP unicast service and the IP multicast service in the case of S4406 Annex E sending the same 2.5 kbyte message to 3 message recipients over an HF channel with an SNR of 6 dB. The IP broadcast data rate is 600 bit/s. The unicast service (left panel) handles the message transfer by sending the messages sequentially to one recipient at a time. The multicast message (right panel) is sent once and is delivered to all the recipients at the same time. The recipient nodes release their P-Mul acknowledgements approximately simultaneously, resulting in all three trying to set up a link to the originator at the same time and creating some havoc on the channel in this process. The S4538 protocol is able to resolve this channel allocation conflict, but it is noted that a very long time is spent for the transfer of the three ACK messages. In the end the originating node broadcasts an End of Message PDU terminating the P-Mul session.

The figure shows that in this given situation, less radio resources are needed when the IP multicast service is used to deliver the message. The message delivery time of the multicast message is about half of the average delivery time experienced when using three unicast messages. However, the P-Mul acknowledgement transfers taking place right after the multicast message delivery, are handled rather inefficiently by the protocols. The accumulated seizure time of the HF channel is still about 40% lower than for the unicast service in the above scenario, thus easing the load on the HF resources. This advantage will increase for an increasing number of message recipients. However, if the channel quality improves, the message transfer times for the unicast service will decrease because of the adaptive data rates, whereas the multicast service is stuck with the fixed data rate. This may change the picture of multicast using HF resources more effectively than unicast.

There are room for performance improvements for the handling of multicast traffic, as regards the implementation of the HF protocols as well as XOmail protocols. We believe that the use of S4406 Annex E combined with an efficient multicast link protocol has the potential of providing attractive solutions for several one-to-many HF communications scenarios.

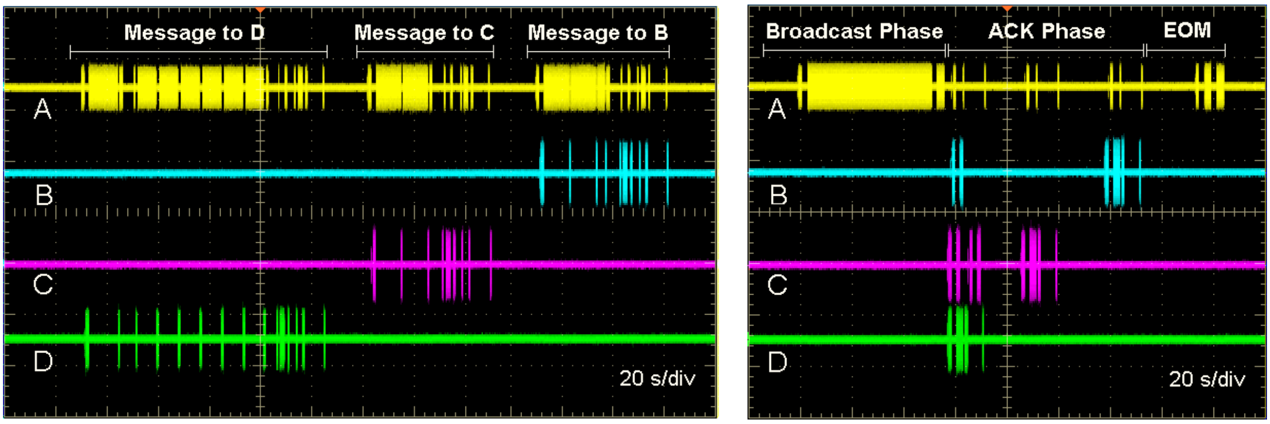

Figure 6. Oscilloscope traces showing the transmissions from the four HF radios when a message is sent to three destination addresses. The left/right panels show the activity when the message is sent as three unicast messages or as multicast, respectively. The upper trace represents the sending node.

5.0 A COMPARISON WITH A DEDICATED HF MESSAGING APPLICATION FOR UNICAST MESSAGE TRANSFER

The results presented so far are all based on the transparent transfer of IP packets carrying S4406 Annex E information wrapped in UDP PDUs over the HF links. There are, however, other options for transferring information over an HF link. As mentioned, S5066 defines a set of Service Access Points (SAP), some of which may be used to map the application information directly to the HF link level. Two of these are optional SAP's defined for use by the HF mail Transfer Protocol (HMTP) and the Compressed File Transport Protocol (CFTP), respectively. Both of these protocols are made for efficient packaging of messages for HF transfer. However, this solution of a direct mapping of the application information to the HF link layer does not provide any networking functionality. Consequently, such a solution is only viable over a one-hop HF link.

It would be reasonable that mapping application information directly to the HF link layer requires less HF capacity than if UDP/IP is involved. Hence it is to be expected that S4406 Annex E using a transparent IP service would be less efficient than using CFTP/HMTP mapped directly to HF. We used the Wireless Message Terminal RF-6710W (WMT) from Harris to send a message with a compressed attachment by CFTP over S4538, so that a comparison with XOmail using transparent IP over HF to send the identical message could be made. However, such a comparison is indeed a bit like comparing "apples and pears", since it does not account for the inherent advantages of the S4406 Annex E with respect to its offering of military services such as security and priority, or to the seamless interoperability it offers with military strategic messaging systems and with military procedures.

The following parameters were compared:

- the message delivery time.
- the total time duration that the HF channel is linked for the complete message transfer. This expresses the required use of HF resources for the message transfer.
- the number of bytes additional to the size of the compressed file that the S4538 has to transfer. This is a measure of how efficient the message is packaged at protocol levels above the datalink layer.

The measurements were made with a channel SNR of 20 dB. Figure 7 shows the measured performance parameters of S4406 Annex E (XOmail) using the transparent IP service over S4538 relative to the measured performance parameters of CFTP (WMT) mapped directly to the S4538 link protocol. It should be noted that the measurements do not only reflect the contributions from the standardized protocols, but are also affected by implementation choices and to some degree by processing times. One such important implementation parameter is the procedures and timer values used in conjunction with IP transfers over S4538. These are not part of S4538, and we believe there is some room for improvements in the efficiency of IP transfers of the measured equipment.

The green curve in the figure shows that the increase in the HF data link payload of the S4406 Annex E is very modest and only occurs for short messages. We assume that this increase may be at least partly explained by the added information that needs to be transferred due to the military services offered. The S4406 Annex E over IP also gives a slight increase of the message transfer time (blue curve). This percentage increase in transfer time grows with increased message size. This is primarily caused by the fact that the S4538 implementation organizes the IP traffic less efficiently than for bulk message transfer. The IP packets are organized in assemblies. Between each assembly there is a time gap in order to allow for channel reversal, and this time gap results in reduced protocol efficiency.

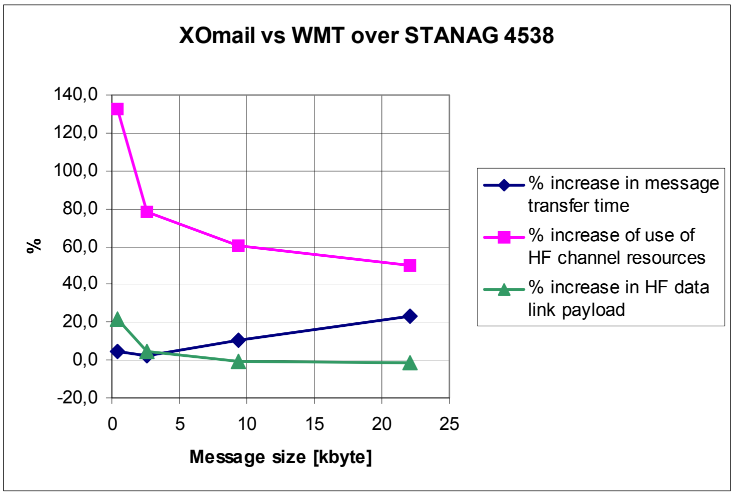

Figure 7. The performance of XOmail using a transparent IP service relative to using the WMT (CFTP) mapped directly to S4538.

The pink curve showing the most dramatic difference is related to the use of the HF resources, i.e the total time that the HF channel is occupied during one complete message transfer. There is a simple reason for this, which is the end-to-end acknowledgment mechanisms which are part of the Annex E protocol. The transmission of a P-Mul ACK in the reverse direction followed by a P-Mul EOM secures the S4406 Annex E message delivery reliability in an optimum manner. However, two channel reversals are necessary to accomplish this, and it is basically these channel reversals/HF link management messages that causes the use of the HF channel resources to increase sharper than the message transfer time. The WMT does not make use of a true end-to-end acknowledgement concept. It conveyed only the one-way message content on the HF channel.

The measured increase in message transfer time and the increased use of HF resources for the measured S4406 Annex E system are to a large extent attributable to its use of a transparent IP service and to the way that this service is handled by the implementation of the HF link protocol. Using the transparent IP service is a general solution, enabling HF to become an integrated part of the tactical internet. However, a solution with application data mapped directly down to the HF link layer will provide some efficiency gains. Such a gain may be provided also for S4406 Annex E systems, since there exists an option for a S4406 Annex E HF subnet interface SAP similar to those defined for CFTP/HMTP. As mentioned, the above comparison only considers the efficiency aspect of the message transfer. It must be kept in mind that important differences in functionality and service level between the systems are not reflected.

6.0 PROPOSALS FOR IMPROVEMENT OF THE P-MUL PROTOCOL (ACP 142)

We have experienced limitations of the current P-Mul protocol and implementation in our testing. A new version of ACP 142 is under development by NATO and the CCEB. Proposals have been made to include new functionality such as end-to-end congestion control, Forward Error Correction (FEC), handling of acknowledgement implosion and more dynamic mechanisms for adaptation of timers to the change in the communications conditions of disadvantaged grids. Since the proposals are still under discussion at the time of writing, some of the proposed functionality will be presented here without going into details.

6.1 Congestion control

In the current version 1.0 of the ACP 142 protocol, there are no congestion control mechanisms specified. The requirement for a congestion control mechanism and how it is solved using the IETF ICMP Source Quench protocol in the XOmail application and the RF-5800H radio is described in section 4.1.2. Since the congestion control problem is at the transmitting side between the application and the radio and not between the sending and receiving application, this form of congestion control is reasonable to use because it addresses the problems locally. However, because the ICMP Source Quench will not be maintained for IPv6, and the potential use of IP crypto will prevent the ICMP Source Quench packet from being transmitted from the radio to the application, another mechanism will have to be chosen. An end-to-end congestion control mechanism is being discussed for the next version of ACP 142. This solution will most likely be based on calculation of the measured delays of the P-Mul PDU's, which then will be used to regulate the flow of PDUs being sent from the P-Mul protocol. Timestamps may be added to some of the P-Mul PDUs in order to log the transfer time, which then is reported back to the sender. Such an end-to-end congestion control mechanism will not be as adaptable to the change in the communication conditions as the local ICMP Source Quench mechanism, because of the delay in getting the response. There are however, not many other alternatives if the use of IP crypto is not to be prevented.

6.2 FEC

An optional FEC mechanism in P-Mul is proposed. The main intention of the FEC is to improve the protocol performance on channels that are susceptible to PDU loss. This is the case when using radio channels with no acknowledgement mechanisms, for example when sending to EMCON recipients or when using a simple multicast protocol on a broadcast channel.

By introducing the FEC mechanism the complete message may be reconstructed by the recipient, even if a certain number of P-Mul PDUs are lost. This will increase the probability of message delivery to EMCON recipients. When using the multicast service with the FEC option, fewer (or no) negative acknowledgements will be required. In some cases, in particular when using HF protocols, the cost of returning an acknowledgment PDU may be high, and a reduction of the P-Mul traffic gives a noticeable performance improvement. On channels susceptible to PDU losses, a shorter delivery time is achievable by using the FEC option.

Reed-Solomon codes have been proposed as a suitable FEC mechanism at the P-Mul layer, due to its flexibility and its powerful error correcting capabilities.

6.3 More dynamic parameters for adaptation to the communication conditions

The current version 1.0 of the ACP 142 protocol uses static parameters that may cause problems when the protocol is used over radio systems with varying data rates end error conditions.

One of these static parameters is the re-transmission timer, which has to be set high if the condition of the channel is varying, in order to avoid premature time outs and retransmissions in the worst-case situations. A proposal has been made to make this timer more adaptable by taking into account the measured round trip delay and the size of the message to be transferred.

Another dynamic parameter proposed is the "Receiver Last PDU Timer". In the current version of the ACP 142 protocol, an acknowledgement is triggered by the reception of the last Data_PDU expected by the receiver. This means that if the last Data_PDU is lost, the receiver will not generate an acknowledgement. This will cause the transmitter to time-out and start re-transmitting the data. The new timer will trigger the generation of an acknowledgement if the last Data_PDU is lost, and will be calculated dynamically based on the arrival time of the previous Data_PDUs.

6.4 Handling Ack Implosion

If a message is multicasted to many recipients, there is a problem that the recipients may start sending acknowlegements at the same time. In radio networks, this may result in collisions because they all try to access the channel. In order to avoid this situation, there is a proposal for the next version of ACP 142 that all recipients are waiting a randomized period of time before sending the acknowledgement.

7.0 CONCLUSIONS

In the migration process towards NATO Network Enabled Capabilities, the MMHS based on STANAG 4406 may offer a seamless connectivity between NATO nations, between strategic and tactical units and between services. The MMHS is a tool for military command and control which, with the inclusion of Annex E, is extended to tactical users. The MMHS application may be used over different networking technologies and bearer services. By using the S4406 Annex E protocol profile we have shown that a reliable and reasonable message transfer is possible over an IP network which comprise an HF link. This opens for an architecture where the HF links may be directly utilized also for IP traffic from various other applications. This is not possible with mail applications dedicated for a specific radio link such as HF. However, the latter solution is able to utilize the HF channel resources more efficiently.

MMHS Annex E over HF systems is a viable solution, providing application throughputs up to a few kilobits per second. However, an HF link will represent a potential “bottleneck” in an IP network and it requires special attention for optimum performance. We experienced congestion control problems when using UDP/IP over a narrowband tactical link such as HF. Acceptable performance was achieved by using a congestion control mechanism based on ICMP Source Quench, but in the long term a new congestion control mechanism is called for.

The multicast functionality of S4406E promises to be an efficient way of delivering one-to-many traffic when used in conjunction with a suitable HF link service. In a simple one-to-many scenario tested, a significant reduction in the mean message delivery time was achieved and less radio resources were needed by transferring the message by an IP multicast service rather than by consecutive IP unicast transfers. The multicast performance can be enhanced further by modifications of the P-Mul protocol as well as in the RF-5800 IP broadcast protocol.

It is important to test complete systems together, ranging from application to the physical link. There are optimisation issues at different levels of the protocol stack, and we have seen that implementation choices and parameter setting have great impact on the overall performance of the system.

8.0 ACKNOWLEDGEMENTS

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