OPEN PACKET RADIO PROTOCOLS FOR HIGHLY SURVIVABLE LAN TO LAN INTERCONNECTIVITY

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ABSTRACT

Both media diversity and open packet radio protocols has been the focus of the STC activities in the area of highly survivable communications (HSC) since the early eighties. Recently a suite of packet radio protocols providing standard OSI Data Link Layer services has been completed and tested on both on-the-air and under laboratory conditions. The STC suite of packet radio protocols provide connectivity over High Frequency (HF) sky-wave, Meteor Burst (MB) and mixed/media (MM) HF-MB radio media. They utilize standard military or commercial hardware equipment and are interoperable with the OSI Connectionless Network Layer Protocol (CLNP).

1. HIGHLY SURVIVABLE COMMUNICATIONS (HSC) USING MIXED MEDIA (MM)

There are growing military requirements for mobile Highly Survivable Communications (HSC) links for Beyond Line Of Sight (BLOS) LAN to LAN interconnectivity. These links must utilize standard Commercial Off-The-Shelf (COTS) equipment for low cost and must be truly mobile.

Applications of such links include the interconnectivity of forward based mobile Headquarters with static base Headquarters. Mobility, robustness and survivability are very important due to the requirement for frequent change of location and operation under adverse propagation conditions including deliberate jamming.

ECCM (Electronic Counter Counter Measures) SATCOM is an obvious solution to the above requirements. Its main disadvantage however is its high cost which under the present and foreseeable budget restrictions makes it unavailable for most applications.

Another solution is to use more traditional BLOS radio media which with the development of digital processors and advanced modem techniques can offer performance which is adequate to meet the above requirements. STC has been experimenting for a number of years with packet radio techniques over two BLOS radio media namely High Frequency Sky-Wave (HF) and Meteor Burst propagation (MB). HF has been traditionally linked with voice communications and low data rate FSK teletype. MB although analysed and studied by many people it was never actually used in the military despite its anti-jamming and easy frequency management properties. There are only a few commercial applications of MB.

Media diversity has been the focus of STC activities for the development of HSC radio links. This approach utilizes the complementarity of two or more diverse media to ensure uninterrupted connectivity even during periods when one of the media performs poorly due to propagation conditions or deliberate jamming. Media diversity allows HSC links to be implemented using relatively low cost COTS equipment. The alternative way of providing HSC using a single medium would require pushing the state of the art of the particular technology in order to provide non-standard high-cost custom made equipment especially designed to provide service under adverse conditions.

HF and MB are especially suited for integration due to their excellent complementary nature and the similarity of RF technology required for implementation. The combination of HF and MB into a HSC mixed/media link offers great advantages over the two individual media. If any of the two media is disrupted due to propagation, persistent interference or equipment malfunction, the other medium automatically offers a somewhat reduced but vital connectivity. Furthermore the anti-jamming properties of the combined media are superior to those of the individual media since a lot more effort has to be expended to disrupt links over dissimilar media as compared to a single medium. Specifically in the case of MB, the jammer has to be located either within Line Of Sight (LOS) distance to the receiver or very close to the transmitter [1].

2. OPEN PACKET RADIO PROTOCOLS

With the exception of the AX.25 protocol which has been widely used in the Radio Ham community there has not been an open non-proprietary packet radio protocol standard. In addition packet radio terminals for HF and VHF were designed as stand alone systems not able to be integrated as part of a broader communications network. In an effort to stimulate activity on open packet radio systems, STC organized two international symposia; one on Packet Radio (18-19 April 1989) and one on Meteor Burst Communications (4-5 November 1987).

In 1989 an OSI HF Data Link Layer protocol development activity was initiated within STC. In 1991 a similar development activity for MB and mixed/media protocols was also initiated within STC. By 1992 the STC HF Data Link Layer Protocol (HF-SDLP) was completed and by 1993 a full suite of STC developed packet radio protocols for HF, MB (MB-SDLP) and HF−MB mixed/media (MM-SDLP) were completed and tested. The full description of these protocols has been published in STC Technical Notes [2,3,4,5,7,8].

All the STC developed protocols are available upon request to commercial or national organizations. The HF protocol has already been provided to a number of companies and to various NATO and government organizations.

All three STC packet radio protocols utilize a common interface and offer standard OSI services to the Network layer. The HF protocol offers both Connection Oriented (CO) and connectionless (CL) link layer services. The MB and MM protocols offer only connectionless link layer services because it was decided that the overhead required by the connection establishment phase over a low capacity medium like MB would substantially degrade the usefulness of the link. Nevertheless, minimum effort is required to extend these two protocols in order to provide CO layer services if required for interoperability. A more detailed description of the STC link layer radio protocols is presented next.

3. STC OSI DATA LINK PROTOCOL FOR HF PACKET RADIO (HF-SDLP)

Due to changing requirements and the availability of high-speed modems utilizing adaptivity and excision, HF communications is destined to play an increasingly significant role in future military communication systems. Both reliability of data communications and available throughput over HF has improved significantly over the last decade with the advent of high-speed single tone modems employing sophisticated signal processing schemes for adaptive equalization and interference excision. Little has been available in terms of an OSI Data Link protocol to utilize the high-speed single-tone modems for packet communications over HF and to support internetworking with CLNP.

STC data link-layer protocol provides robust and efficient packet communications over HF channels using standard multi-rate single-tone HF modems. The protocol conforms with the OSI description of a connection-oriented link layer service and incorporates features specifically designed for the HF environment [2].

This protocol will be used for the transatlantic HF sub-network (STC-Canada) of the Communications Systems Network Interoperability (CSNI) multinational project (and possibly other HF subnetworks). The CSNI project will also demonstrate packet radio (PR) interoperability with satellite links and other tactical and commercial networks.

The HF OSI Data Link protocol developed at STC provides both CO and CL Data Link Services. The protocol supports multiple Data Link users (up to 20 in the present implementation) simultaneously over a single radio channel.

Both half-duplex and full-duplex HF modem operation can be supported by HF-SDLP. The protocol is intended for point-to-point use and does not incorporate any frequency management or Automatic Link Establishment (ALE) functions. The protocol design offers the flexibility to implement these functions according to the specific requirements of the user.

An important form of adaptivity incorporated into the protocol (in addition to a selective automatic repeat request (ARQ) mechanism) is adaptive control of the modem speed. Extensive testing [3] has shown that the throughput achievable using an adaptive speed mechanism and a judiciously chosen but fixed link-layer frame length is very nearly as great as that which can be achieved when both the modem speed and frame size are made adaptive. A second major feature of the protocol is the incorporation of a mechanism that reduces the frequency of collisions when used with half-duplex radio equipment. Additional features of the protocol include packet segmentation, use of low-overhead frame structures and a prioritized channel access scheme for networking applications.

Some of the important features of the HF-SDLP are summarized below:

- Adaptive modem speed control.

- Selective automatic repeat request (ARQ).

- Collision avoidance and collision recovery mechanisms to reduce the probability and effects of collisions occurring over half-duplex links.

- Segmentation of long data packets.

- A single byte "connection reference number" rather than the full link address is carried by the link-layer frames to minimize the overhead.

- Prioritized channel access for connection-oriented Data Link Service.

- Robust connection management and data acknowledgement procedures.

The STC HF Data Link protocol has been implemented in software [4] and tested extensively in the laboratory environment using ionospheric channel simulators. Simulator testing was used to establish the performance of the protocol using standardized channel conditions and enabled performance comparison with the performance of the AX.25. The protocol is particularly suitable for use with the new generation of adaptively equalized, single tone HF modems (NATO STANAG 4285, US MIL-STD-110A) [9,10] and the results presented below are with such modems.

The STC HF Data Link Protocol was tested on-the-air using a link between STC and the remote site in Staelduinen. The Staelduinen site is located at a distance of 25 km from STC. The tests on this link were done in daytime hours at a frequency of 6.98 MHz. Past experience and observations made during the trials indicated that, at the frequency used during these tests, propagation was solely via sky-wave. No attempt was made to change the frequency in order to optimize the performance. During the test period, this frequency supported sky-wave communications on the test link starting around 9.00 a.m. The sky-wave link terminated shortly after the sun set, around 5.30 p.m.

The on-the-air tests were carried out in the half-duplex mode. The averaging period for the throughput measurements was 30 min. The tests were conducted over a time period covering December 1992 and February 1993. Throughput measurements were made in half hour slots beginning at 9.30 a.m. and ending at 5.00 p.m.

The one-way throughput measurements recorded in the half hour slots during the test period were averaged for each time slot and shown in Fig. 1. The number of measurements made on each half hour slot during the test period are also displayed in Fig. 1. As indicated in Fig. 1, the throughput averaged over the test period was relatively low at 9.30 a.m., due to weak propagation, but then increased to 1400 bps at 10.00 a.m. Between 10.00 a.m. and 4.00 p.m. the average throughput fluctuated between 1200 bps and 1600 bps. After 4.00 p.m., the average throughput gradually decreased due to the combination of interference and worsening propagation conditions.

The significance of the results shown in Fig. 1 is that even without frequency management a high average throughput (above 1200 bps) could be sustained over a continuous 6 hour daytime period. There were observed instances of interference and weakening of propagation during the test period. The remedy for such impairments is of course frequency management, which is considered as a necessary component of a complete system design.

Some on-the-air test data was also obtained on a link between STC and Latina, Italy (approximately 1400 km). These tests were part of a mixed/media measurement campaign. The HF OSI Data Link protocol was tested on this link on a daytime frequency of 14.69 MHz. Throughput measured over 30 minute periods was recorded during different times of the day. The measurements covered a period of four days, 21,23,24 and 25 June 1993. Some of the data obtained during these trials is shown in Fig. 2. Similar to the Staelduinen test results, the average throughput was high, with occasional periods of lower throughput due to interference or weak propagation. Further multi-hop links with US and Turkey are being planned.

Overall these results and others not discussed here have shown that sustainable average data rates in excess of 1 kbps over difficult short links (high angle sky wave) and more typical long distance links, is readily obtained with simple frequency management. With more sophisticated frequency management, for example using automatic link establishment/maintenance (ALE/M) techniques, the protocol can be expected to provide throughput approaching 2 kbps (excluding ALE/M overheads).

4. STC OSI DATA LINK PROTOCOL FOR METEOR BURST COMMUNICATIONS (MB-SDLP)

This full-duplex protocol is a culmination of much analysis and experience over real links accumulated at STC over the past years. It is the result of a pragmatic systems level approach rather than an attempt to push the state of the art of MB systems through sophisticated signal processing approaches. The absolute requirement was that the protocol must be open in the OSI sense be easily integrated into the OSI network layer as in the HF-SDLP case.

The link layer issue that is probably the most important in defining a MB protocol is the manner in which channel probing should be implemented. This process determines the availability of suitable trails between the transmitter and receiver so that data transmission can immediately start [1,6]. The two basic approaches are:

(a) utilizing special short probing frames or packets,

(b) using data frames themselves to probe the channel.

After extensive study of the related trade-offs, STC experimental results and the information available from other sources, it was concluded that there is a very small advantage in using special probing frames. However, this small advantage can be negated by the additional complexity and processing time requirements [6]. The STC protocol, therefore, implements implicit probing with the data frames in the transmit queue. This permits efficient operation with standard PC processing through a robust, generic single frame type in both directions. The frame structure has sufficient flexibility to handle all necessary functions. More detailed information can be found in [7].

The other features that make this protocol efficient for use on MB links are:

1. Selective ARQ (automatic repeat request) is used as opposed to go-back-N. This ensures that all frames with good CRC check are utilized.

2. Acknowledgement (ACK) information about all received frames are piggy-backed on the data frames.

3. Quick reset procedure is provided to flush both transmit and receive queues.

4. Fast modem synchronization: user selectable number of preamble characters is transmitted before each frame.

A number of timers are also implemented to cater for the occurrence of small probability but possible events. Two most important are:

(a) **NO_ACK** timer: If the time since the last received ACK exceeds this timer duration (user selectable with default = 15 min) the transmit buffer is flushed and transmission stops. Next data frame transmitted has reset bit set.

(b) **NO_DATA_RX** timer: The receiver keeps sending ACK frames for the duration of this timer setting (user selectable with default = 15 min) after it has received the last valid data frame. This ensures that the transmitter will receive the last ACK. For non-bursty channels this timer can be set to a few seconds.

Like the HF protocol described above, this MB protocol can also run stand-alone, accepting data from a keyboard/PC or can be interfaced to a higher layer protocol to which it offers CL data link layer services. PDUs (Protocol Data Units) given to the MB link layer by the network layer are buffered, segmented if necessary and transmitted. At the receive end converse is performed and the PDUs are reassembled and given to the Network layer in the same order they entered on the transmit side.

The protocol has been and is being used with 5 kbps DBPSK modems built at STC during older MB experiments. The protocol can however be used with any modem with a standard synchronous RS-232 interface.

Results of tests and on-air trials performed with this protocol indicate that throughput obtained under various conditions are at least comparable to published results with other (proprietary) protocols. Because STC work is focused on the use of MB as component of a mixed/media HSC system we will present the results as a component of our MM activities in the following section. These indicate that, both as a stand-alone MB data-link protocol and as a component of a mixed/media service the results are very satisfactory. The implementation is possible with standard hardware, the protocol is open and can be provided to any NATO entity to enable interoperable MB communications.

5. STC MIXED MEDIA PROTOCOL - HF/MB (MM-SDLP)

This protocol or mixed-media controller efficiently combines a MB link and an HF link into a new "virtual link" which offers all the advantages of mixed/media operation. HF and MB are especially suited for integration as a MM unit because of excellent complementary nature of the two media and the similarity of the RF technology required for implementation.

Specifically:

- The MM link is more robust. If any of the sub-link media fail due to propagation, persistent interference and/or malfunction the other will automatically offer connectivity.

- Anti-jamming properties are greatly improved. A great deal more effort has to be expended to disrupt links over dissimilar media as compared to a single medium. Specifically, in the case of MB, the jammer has to be located either within radio LOS to the receiver or very close to the transmitter [1].

- With both media operating the throughput is the combination of throughputs of both media or sub-links.

- One link can be used as electronic order wire (EOW) if there is a problem with one of the media. In this special case of HF/MB, the latter can provide frequency change information as the HF link deteriorates and/or initiate an ALE operation.

All the above advantages are gained through the use of standard, low-cost COTS hardware. Equivalent levels of robust connectivity through the use of a single medium would require the development/procurement of expensive customized systems.

If two media like HF and MB are to be combined efficiently, real time information about their performance must be available. Any algorithm based on a-priori statistical information would not be adequate due to the continuous and dynamic changes in the propagation characteristics and interference environments of these two media. The STC MM protocol (MM-SDLP) monitors the ARQ process of the two individual media in order to determine the rate at which they are successfully delivering frames. The MM-SDLP keeps active updated copies of the frame queues of the individual media at all times. A frame is given to a link for transmission if its queue size is less than a predefined max size and if the link has not ordered MM-SDLP to stop the flow of frames. If at any time the queue size reaches its maximum size the link does not receive any frames until its queue is reduced.

MM-SDLP does not introduce any ARQ process of its own, it simply relies on the ARQs of the individual links. The protocol needs only 2 bytes of overhead per frame. The frame sequence number is restricted to the range 0-255 and thus the maximum transmit window size is 128. The aperture of the Tx window (difference between the numbers of the first and last frames) can not be greater than 127.

An important feature of the protocol is the fact that the frames delivered to the individual links are "not forgotten". If a frame has been "stuck" in a link then MM-SDLP automatically enters its "robust" mode. In this mode, all frames stuck in the slower medium are also given for transmission to the faster medium so that all possible resources are applied to push through the stuck frames. A frame is considered stuck if one of the following low-probability but possible events occur.

- A frame has been in the queue of a link for a duration of greater than a prespecified value (default = 3 min, but user selectable).

- Frames are available for transmission, at least one medium is free to accept frames but the aperture of the Tx window has reached its maximum value 127 because the first frame of the Tx window is stuck in the queue of the other medium.

After stuck frames are given to both media, eventually they are ACKed. As soon as this happens both media queues are flushed to avoid retransmissions of already ACKed frames and the MM-SDLP returns to its normal mode, giving frames to the individual links according to the rate at which they can successfully deliver them.

The transfer between the normal and the robust modes occurs automatically and in a way which is transparent to the higher layers. As seen by the network layer, the MM-SDLP provides a CL link layer service. MM-SDLP is totally responsible for the combination of the heterogeneous links as efficiently as possible and guarantee reliable delivery of the frames.

MM-SDLP can also run stand-alone with messages generated locally by an operator or can be interfaced to a network layer, as with the other STC packet radio protocols. Figure 3 shows the position of the MM-SDLP in the OSI stack. Figure 4 gives a schematic diagram of the STC MM testbed. Messages to be transmitted by the MM system can be originated by users on a standard LAN interfaced to MM-SDLP through a router as shown in Fig. 4.

Figures 5 and 6 present actual on-air test results over a 1400 km link between STC and Latina (Italy). Figure 5 gives the average throughput in bps in 30 minute blocks of measurements, individually, over the two media, HF and MB utilizing the protocols described in Sections 3 and 4 above. No attempt was made to improve the night time HF performance through better frequency management, intentionally, so that the complementary nature of the two media could be clearly exemplified. As seen in Fig. 6 combination of the two media through MM-SDLP as described above, ensures continuous connectivity with throughput ranging between highs of few kbps (corresponding to sporadic-E on MB and/or good HF conditions) to lows around 50 bps when only low trail density MB is the only available option. Figure 6 exemplifies a non-typical period during which the MM link is forced to rely on only one media for an extensive period. Normally both links contribute to the throughput in a more dynamic way. With the enhancement of the HF link frequency management the contribution of the HF sub-link during the night-time hours (Fig. 8) would be greatly improved. More detailed information on these tests is available in [8].

6. FUTURE WORK

Current and Future work on packet radio protocols at STC is focused on the following main areas:

1. Implementation of HF frequency management techniques using MIL-188-141A ALE.

2. Implementation of the STC-Canada transatlantic HF link which will form part of the overall internetwork developed under the Communications Systems Network Interoperability (CSNI) multinational project.

3. Porting of the protocols on a variety of platforms, including PC/DOS, PC/UNIX, VME/-VxWorks, TMS320.

4. Modification of the protocols to provide TC-P/IP interconnectivity in addition to OSI. This is viewed as a very important step towards interoperability due to the vast amount of TCP/IP applications and the size of the TCP/IP internetwork world.

5. Provision of several levels of security. This effort has been recently initiated and it has been stimulated by the increasing interest on the STC packet radio protocols. Several ways of security provision are being investigated from the simple insertion of a crypto device between link and physical layers to more advanced methods which will require substantial modifications to the protocols.

7. CONCLUSIONS

Responding to the growing requirements for open packet radio protocols capable of interoperating with other communication systems and forming part of an overall communications internetwork, STC has developed a suite of protocols for HF, MB and HF/MB Mixed-Media.

These protocols provide standard OSI services to the Network layer and can be implemented using low cost COTS hardware equipment. All protocols have been optimized for their respective radio media and are the result of many years of practical experience accumulated at STC. The MM protocol efficiently combines HF and MB in a way transparent to the user and achieves survivability under adverse conditions by exploiting the complementary nature of the two media and the inherent anti-jam properties of MB.

A HF/MB testbed was implemented at STC using the packet radio link layer protocols described here. Laboratory and on-the-air tests were carried out and results were presented.

The overall conclusion is that OSI protocols and low cost COTS technology can be combined in order to achieve interoperable BLOS mobile radio data links which are capable of providing highly survivable connectivity by utilizing two very important aspects of survivability, media diversity and internetworking.

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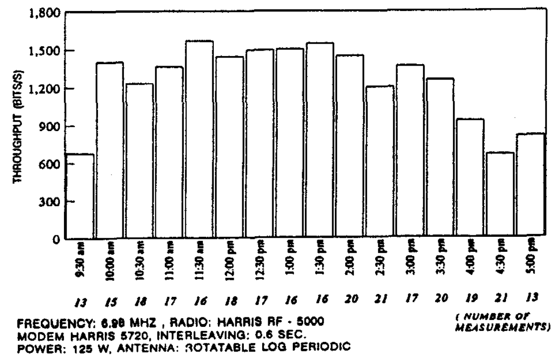

Figure 1. STC-Staelduinen HF trial results.

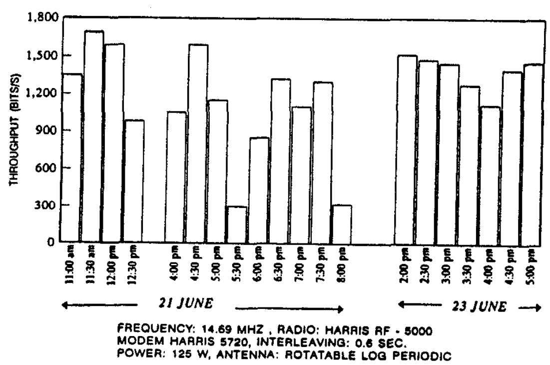

Figure 2. Staelduinen-Latina HF trial results.

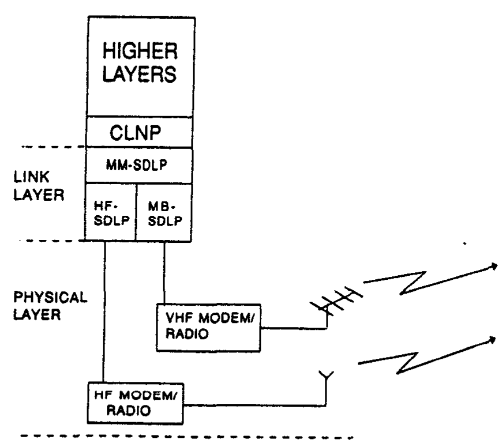

Figure 3. Relative position of MM-SDLP sublayer in the OSI stack.

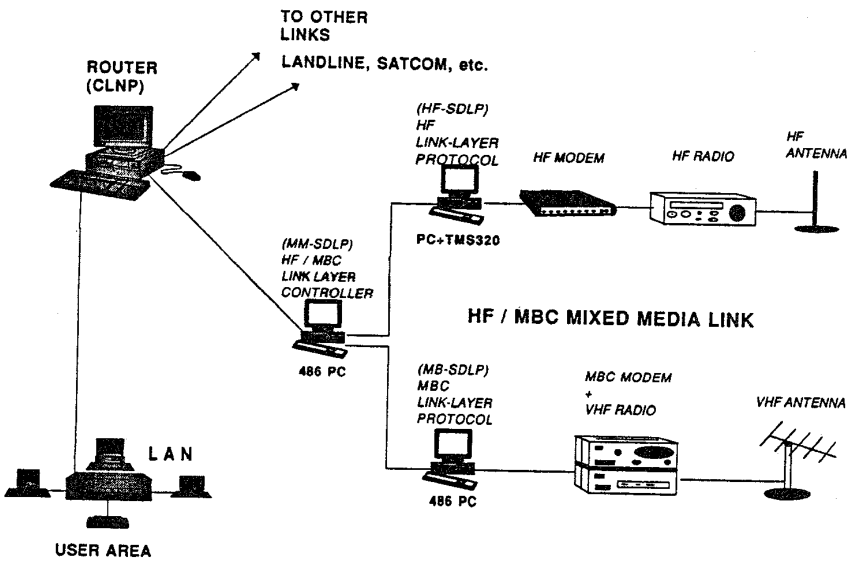

Figure 4. STC Mixed-Media Testbed.

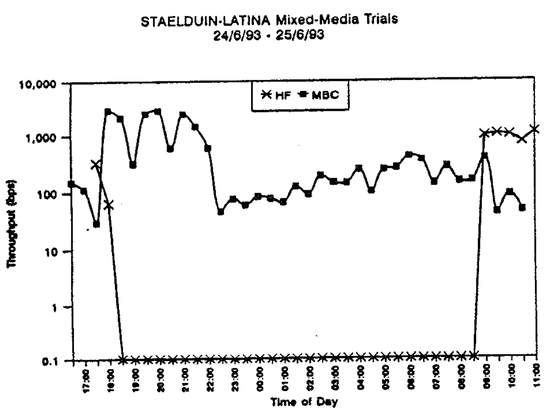

Figure 5. Staelduinen-Latina MM trial results.

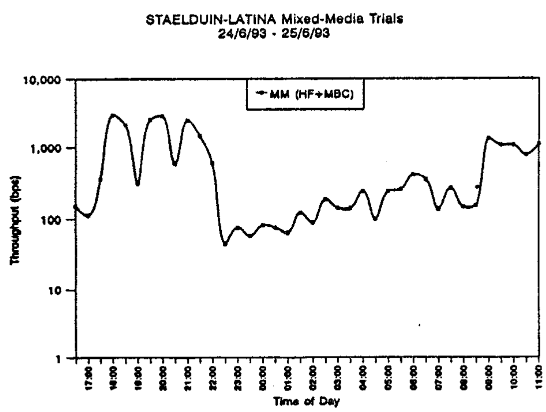

Figure 6. Staelduinen-Latina MM trial results.