A European Mobile Satellite System Concept Exploiting CDMA and OBP

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ABSTRACT

This paper describes a novel Land Mobile Satellite System (LMSS) concept applicable to networks allowing access to a large number of gateway stations ("Hubs"), utilising low-cost Very Small Aperture Terminals (VSATs).

Efficient operation of the Forward-Link (FL) repeater can be achieved by adopting a *synchronous* Code Division Multiple Access (CDMA) technique, whereby inter-code interference (*self-noise*) is virtually eliminated by synchronizing orthogonal codes. However, with a transparent FL repeater, the requirements imposed by the highly decentralized ground segment can lead to significant efficiency losses. The adoption of a FL On-Board Processing (OBP) repeater is proposed as a means of largely recovering this efficiency impairment.

The paper describes the network architecture, the system design and performance, the OBP functions and impact on implementation.

The proposed concept, applicable to a future generation of the European LMSS, was developed in the context of a European Space Agency (ESA) study contract.

INTRODUCTION

Among the LMSS concepts currently being evaluated by European space communications organizations, considerable interest is being paid to the possibility of sharing a K_u-band VSAT as the Hub of a **private** *mobile-service* network and as the Hub or User Terminal of a *business-service* network (use of multi-purpose or colocated satellites is assumed). The mobile-service sub-network will also allow access to **public** Hubs, interfaced to the terrestrial network, for which the low-cost constraint could be somewhat relaxed.

As widely discussed in the literature [1] [2] [3] [4], CDMA can improve the LMSS spectral efficiency; in particular the so called *synchronous* version of CDMA can result in even higher efficiency. The actual CDMA system capacity advantage is larger when the number of mobile-link beams is high and if voice activation and low-rate FEC encoding are adopted.

In contrast to the FL, the adoption of synchronous CDMA for the Return-Link (RL) is considered to be questionable, due to the difficulty of maintaining mobile terminal synchronization in the harsh LMSS propagation environment, and recourse is likely to be made to the more traditional *asynchronous* version.

Although the expected symmetrical FL / RL capacity requirements may lead to questioning of the utilization of different techniques for the two links, for a non band-limited system the higher synchronous CDMA spectral efficiency can be easily translated into a reduction of the RF power-per-channel requirement for the FL repeater. This is evident from fig. 1, showing a comparison between asynchronous and synchronous CDMA for the network configuration which will be illustrated later. For a nominal repeater capacity of 3,200 channels, corresponding to the power-limited capacity of the RL re-

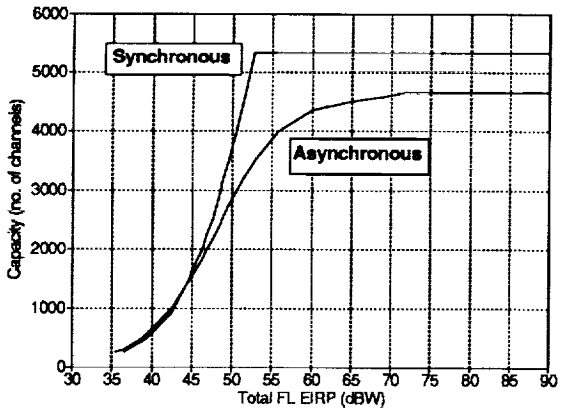

Fig. 1 EIRP requirements comparison

peater operated with asynchronous CDMA, a power saving of about 3 dB can be gained.

The above led to the definition of a LMSS concept, consistent with a highly decentralized ground segment, and making use of synchronous CDMA on FL and asynchronous CDMA on RL as a means to combine high spectral efficiency with savings in FL on-board RF power.

The concept was developed with reference to a geostationary satellite featuring a 6-beam L-band mobile link and a single Euro-beam K_u-band feeder link. This configuration is representative of a possible LLM follow-on payload, LLM being the LMSS subsystem to be flown aboard the European ARTEMIS satellite. A bandwidth of 7 MHz and an L-band EIRP of 49 dBW were assumed to be available. The peak antenna gain is in excess of 36 dB.

The available 7-MHz bandwidth is subdivided into 1-MHz segments, thus supporting 7 distinct CDMA accesses. The same 7-MHz band is re-used in each of the 6 beams, exploiting the CDMA interference rejection properties, thus leading to a total of 42 "CDMA modules". This approach was selected to provide compatibility with the first-generation European LMSS payload (EMS) and for gradual bandwidth utilisation, proportionally to traffic demand.

RATIONALE FOR USE OF OBP

Synchronous CDMA implies that Hubs should be designed to support both a clock and a carrier frequency loop so as to not impair the codes cross-correlation properties. The transmit chip phase has to be controlled within a fraction of a chip (typically less than 100 ns), while the transmit carrier frequency must be maintained within a fraction of a symbol period (roughly ±500 Hz for a K_u-band up-link)

Another and more important problem concerns overhead, in terms of RF power, deriving from the need for FL Pilot Carriers (PCs). With CDMA, the Hub has to transmit a spread, although unmodulated, PC synchronous, at both *clock* and *carrier phase* level, with its traffic codes. The PC must be transmitted at a level at least 5 dB higher than the traffic codes, in order to allow dependable carrier recovery at the coherent mobile terminal demodulator and to maintain robust receive code synchronization.

Each Hub has to transmit its own PC, due to the practical impossibility for Hubs to synchronize their traffic codes, at *carrier phase* level, to a unique PC which could conceivably be transmitted by a Network Coordinating Station (NCS). If the number of Hubs is large, the PCs overhead also becomes large, thus significantly impairing the overall system efficiency.

This problem becomes particularly important for the system under consideration, featuring multiple L-band beams and bandwidth segmentation into CDMA modules, as the total number of PCs needs to be further multiplied by 42.

Fig. 2 shows how the PC overhead degrades capacity, for a variable number of Hubs. Fig. 2 also includes the extra overhead due to the need for each Hub to transmit a Signalling Carrier (SC) per CDMA module.

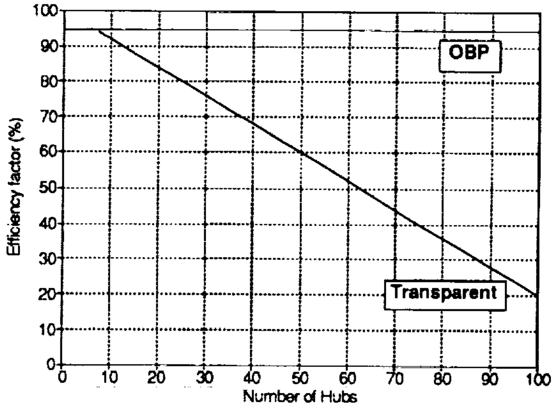

Fig. 2 System efficiency vs number of Hubs

As a final issue, the high CDMA capacity is achieved at the expense of a large feeder-link bandwidth. It can be easily seen that, to be able to independently address the 7 1-MHz CDMA modules in each of the 6 beams, a total feeder-link of 42 MHz is required (32 MHz would be required with FDMA to accommodate 3,200 channels with 10 KHz spacing).

An OBP repeater, featuring on-board generation of CDMA codes, offers an attractive solution to all the above problems, in that:

- the Hub access technique can be selected such as to simplify Hubs;
- a single PC for each CDMA module can be generated on-board, this clearly being coherent with the on-board generated traffic codes;
- the feeder-link bandwidth can be reduced by using a band-efficient access technique.

With OBP on the FL, the overall PC overhead becomes virtually independent of the number of Hubs and equal to a well affordable 5.3% (minimum), corresponding to a 0.23 dB loss.

In addition, the FL OBP repeater allows the efficient call routing (in Erlang terms) to spots, as on-board resources form a pool common to all spots, with sharing on a call-by-call basis.

The RL repeater was instead assumed to be transparent for the following main reasons:

- the RL topology (many-to-one) offers little room for gaining Erlang advantages;
- the complexity of implementing a large bank of on-board CDMA demodulators;
- moderate advantages to be gained, in terms of absolute power, e.g. by routing all up-link traffic in a single TDM down-link stream.

Nevertheless, RL OBP could still be considered attractive for reducing the down-link bandwidth requirement, for simplifying the Hub receive side, for allowing direct mobile-to-mobile calls (no double-hop via hub station) and to achieve some link performance improvements.

L-BAND DOWN-LINK DESIGN

The 7 CDMA modules of a spot beam all utilize the same family of preferentially-phased Gold codes; this configuration results in virtually no *self-noise* both because the selected codes are nearly orthogonal and because of the frequency-staggering arrangement. However, because the same codes are also used on the co-frequency CDMA modules of the other spots, some interference is generated (*cross-noise*).

Should the "other" spots codes be in phase with the "wanted" beam codes, cross-noise would be only limited by antenna discrimination, reducing to an unacceptable 0 dB at spot beam cross-overs. For this reason, it is proposed that codes operating on the other beams be shifted with respect to each other by 1/6th of the code length, thus taking advantage of an additional isolation factor.

This is feasible because of the good Gold codes self-correlation properties, resulting in a cross-noise nearly equivalent to that of random codes. This would have not been the case if Walsh functions had been selected, because these require an additional level of spreading to avoid interference peaks among codes operating in different spots.

The selected CDMA access operating parameters are shown in tab. 1.

Tab. 1 L-band down-link parameters

Vocoder rate	*4,800 bps*
FEC	*convolutional, rate 2/3*
Coded rate	*7,200 sps*
Chip rate	*914.4 Kchip/s*
Processing gain	*127 apparent, 190.5 effective*
Modulation	*BPSK with coherent demodulation*
Spreading	*BPSK*
Number of codes	*127 per CDMA module*

The use of a power-flexible antenna design (e.g. MultiMatrix Amplifier or Imaging Phased Array), allowing dynamic sharing of available on-board RF power among spots to match the current traffic level in each spot, is required to support the inherent system tolerance to traffic imbalance across spots. The availability of 7 CDMA modules gives a spot the capability of supporting a peak of 889 channels, i.e. 67% more than the average capacity in balanced traffic conditions.

K_u-BAND UP-LINK DESIGN

The preferred choice for Hub access is dual-rate TDMA (separate access channels for each rate). This results in the:

- minimization in number of modems both on-board and at Hubs;
- possibility of tailoring the access rate on the total Hub traffic and cost constraints (low-rate for private Hubs and high-rate for public Hubs);
- possibility of still supporting an adequate total private traffic level, by means a frequency-staggered multi-channel TDMA arrangement;
- fairly high flexibility to reassign capacity to Hubs. In particular, the proposed modular frame allows the reallocation of capacity blocks without having to upset the burst time plan.

The main TDMA access parameters are presented in tab. 2.

Tab. 2 K_u-band up-link parameters

	Private Hubs	Public Hubs
TDM access rate	*3.072 Mbps*	*24.576 Mbps*
Number of up-link carriers	*16*	*1*
Total access capacity	*2,304 channels*	*2,304 channels*
Max. Hub capacity (per TDMA carrier)	*144 channels*	*2,304 channels*
Frame elementary module	*4 channels*	*6 channels*
Frame efficiency	*33.8 %*	*67.5 %*
Antenna diameter	*2.5 m*	*3.5 m*
RF power	*13 W (1 carrier)*	*50 W*

The following is noted:

- the capacity of each access (2,304 channels) exceeds by 44% half of the repeater capacity thus leaving flexibility in accepting different private / public traffic sharings;
- re-allocations of capacity blocks need not be performed on a call-by-call basis, because of the fairly small block size;
- the fairly low frame efficiency results from the simple burst synchronization schemes; for private Hubs it was assumed that the TX start-of-frame (SOF) will be derived by adding a fixed delay to the RX SOF, while for public Hubs the delay will be adjusted on the basis of the current satellite position (open-loop control);
- interleaving and FEC coding are performed on a per-channel basis by Hubs, thus relieving the OBP from this task. A coding gain close to the soft-decision one can be attained, the up-link BER performance (10^{-4} @ 99.5% of time) being much better than that of the down-link;
- scrambling is performed at bundle level, assuming the presence of a de-scrambler following the on-board demodulator;
- voice activity will be detected at Hubs, inserting appropriate flags in their bursts, to allow OBP to suppress idle CDMA codes. Also a signalling channel is embedded in up-link bursts;
- no Reference Burst (RB) shall be transmitted from ground, due to the availability of a RB transmitted by the OBP into the RL down-link.

THE FL OBP REPEATER

Fig. 3 shows a payload functional diagram, with the FL OBP section being shown in more detail than that of the transparent RL.

A single TDMA demodulator is used for the 24.576 Mbps stream, while a Multi-Carrier Demodulator operates on the 16 3.072 Mbps streams. Frame Processors perform frame and clock alignment and multiplexing, thus generating two identical 17.023 Mbps streams.

An inherently non-blocking T-stage switch routes, on a call-by-call basis, incoming time slots to any of the 42 914.4 kbps output streams. The T-stage effectively performs space switching and concentration functions, by terminating unused up-link slots.

Each of the 42 streams, supporting 127 channels, is fed to a distinct CDMA Multi-Carrier Modulator, which modulates and spreads 127 channels and generates a PC and a Signalling Carrier, all with common hardware.

The 42 CDMA bundles are then associated in 6 groups of 7 bundles, each group being fed to a different spot via IF and RF devices.

The RL is basically transparent apart from the on-board signalling and RB carrier generator. Signalling information is generated by the On-board Network Controller (ONC). This carrier is frequency multiplexed with up-link signals converted at IF.

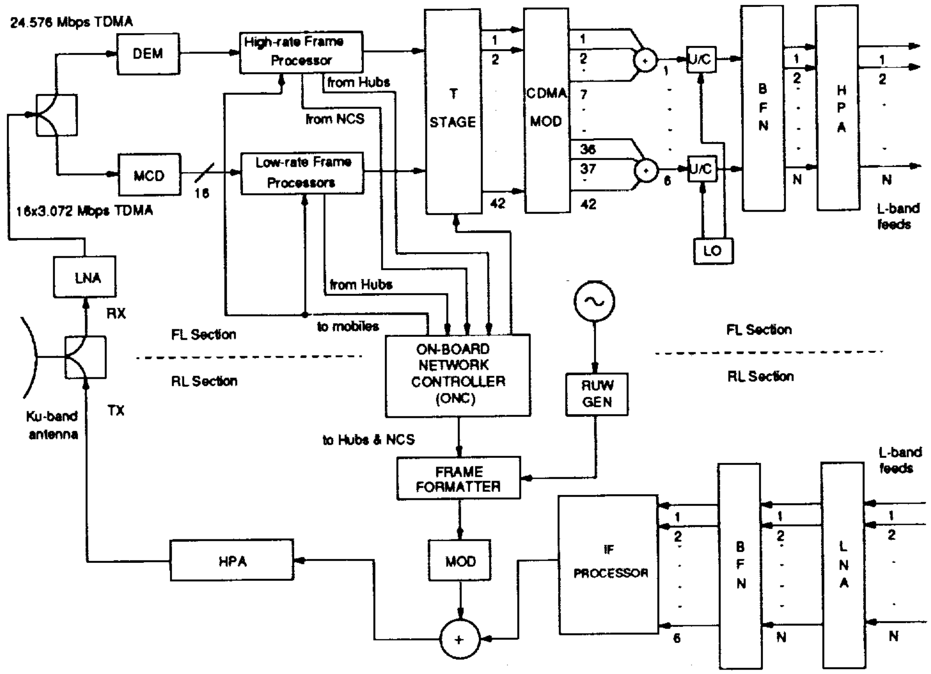

Fig. 3 Payload functional diagram

The ONC manages call handling protocols, by exchanging signalling with Hubs and mobile terminals (mobile signalling is processed at Hubs, the RL repeater being transparent).

SYSTEM ASSESSMENT

With the available 49 dBW EIRP, the overall L-band spectral efficiency of the proposed system is about 2.2 bps/Hz when the traffic is uniformly distributed over the 6 spots. This is considerably higher than that achievable with asynchronous CDMA (1.8 bps/Hz) or with conventional FDMA (0.95 bps/Hz) under the same network, payload and traffic assumptions.

The FDMA system capacity would be band-limited, so that a higher code rate (3/4) has been assumed for this comparison case. In this way the FDMA and the synchronous CDMA approaches would both have the same on-board FL RF power-per-channel requirement of about 19 mW (the cross-noise degradation in CDMA almost equals the lower coding gain in FDMA).

The effect of uneven traffic distributions was assessed by means of event-driven computer simulations, the main results of which are summarized in fig. 4. It is evident how synchronous CDMA possesses an inherently higher tolerance of traffic imbalance across spots than asynchronous CDMA, up to the point where all the available 127 codes are used (this condition is indicated by a dashed curve). If desired, this limit could be pushed further by selecting a different code length and modulation / coding parameters.

It is important to remark that the proposed CDMA system shows an inherent flexibility with regard to traffic patterns, in that uneven distributions can be accommodated without having to reconfigure the FL payload, as would be the case with a traditional FDMA repeater.

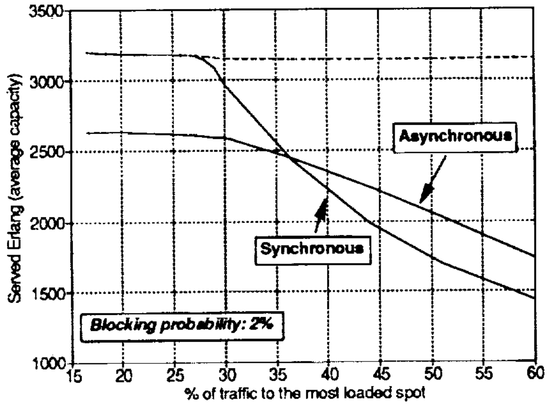

Fig. 4 System capacity vs traffic imbalance

As far as implementation aspects are concerned, a detailed payload modeling activity was performed to derive mass & power estimates and to determine the most suitable implementation technology.

The results of this analysis are shown in tab. 3, which indicates the mass and power of the FL and RL processors as percentage of the overall payload.

Tab. 3 Relative processors mass and power

	Mass (%)	Power (%)
Forward processor	*9.7*	*10.8*
Return processor	*4.1*	*2.0*
Total	*13.8*	*12.8*

It is evident that the FL OBP processor takes about 10% of the overall mass & power resources. In judging this figure, one has to also take into account that, even if OBP is not endorsed, an analogue processor would anyway be required to route channels to spots, thus reducing the proper OBP overhead to a few percent of the overall payload.

From the technology standpoint, a total count of 202 ICs was estimated, assuming the use of a 0.8 μm rad-hard CMOS fabrication process.

CONCLUSIONS

This paper demonstrates that the capacity of a regional Land Mobile Satellite System can be significantly improved by adopting a synchronous CDMA technique in the Forward Link, assuming that the system operates in the power-limited region, this being a typical condition for LMSSs.

The use of an On-Board Processor generating the CDMA codes on-board was shown to be able to further enhance the capacity of a system operating in conjunction with a highly de-centralized ground segment, featuring a large number of gateway stations (Hubs). OBP also yields the remarkable advantage of simplifying the Hub design and hence of limiting their cost.

The proposed system has been designed with particular care as to its adaptability to support uneven traffic distributions across the L-band spots, such as to make it able to operate efficiently under different traffic distribution patterns. The main technique used to achieve this is that of oversizing the internal payload paths, taking care to not cause adverse impacts on processor mass and power budgets.

As a result the FL processor only takes about 10% of the overall payload resources, a fraction of which would anyway have been used if an analogue processor were to be selected, in conjunction with a transparent repeater, to be able to route the up-link channels to the six down-link spots.

The implementation of the processor was assessed and considered to be well within the today's technology status.

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