# Advanced Multiple Access Concepts in Mobile Satellite Systems

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## ABSTRACT

The paper expands upon some multiple access strategies for Mobile Satellite Systems (MSS), as investigated in the frame of three separate studies for the International Maritime Satellite Organisation (INMARSAT) and European Space Agency (ESA). SS-FDMA, CDMA and Frequency-Addressable Beam architectures are addressed, discussing both system and technology aspects and outlining advantages and drawbacks of either solution with associated relevant hardware issues. An attempt is made to compare the considered options from the standpoint of user terminal/space segment complexity, synchronization requirements, spectral efficiency and interference rejection.

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The opinions expressed in the paper, although related to the mentioned study contracts awarded to Telespazio, are not necessarily those of INMARSAT and ESA.

## 1. INTRODUCTION

Next generations of multibeam Mobile Satellite Systems (MSS) are expected to extensively utilize on-board routing and processing functions, to cope with the expansion of user communities demanding MSS services and the possibility of efficiently routing the signals under variable traffic pattern conditions. The latter substantially calls for proper *flexibility* of the system to adapt itself to different scenarios, at the same time minimizing the on-board/on-ground hardware complexity to keep the service rendering cheap and user friendly.

The selection of the better suited multiple access technique is a crucial issue in that respect, associated to the selection of modulation/coding schemes and (possible) on-board regeneration, decoding and switching at channel level. Incidentally, this was indeed the rationale behind an ESA Request for Proposal ("Applicability of different on-board routing and processing techniques to a Mobile Satellite System"), issued in March 1990.

Three possible access schemes are addressed in this paper, on the basis of some studies carried out by the author on behalf of Telespazio. The first one concerns Satellite-Switched Frequency Division Multiple Access (SS-FDMA), and is treated in section 2. The second concerns Code Division Multiple Access (CDMA), addressed in section 3 - although Direct Sequence (DS) spread spectrum is generally envisaged in such systems, we report some investigations on Frequency Hopping (FH) techniques, popular in military applications but not really in satellite CDMA systems -. Section 4 briefly considers the Frequency-Addressable Beam (FAB) concept as applicable to the present context, although only some qualitative comments can be made at this stage since the bulk of investigations performed so far concerned Data Relay Satellites (DRS), where the extremely small number of envisaged users suggested a mixed frequency/phase address scheme. Finally, section 5 attempts to make some comparison among the mentioned access schemes, and some conclusions are drawn.

## 2. SS-FDMA

The viability of SS-FDMA techniques for MSSs has been investigated in several studies carried out in USA, Canada, Japan and Europe.

An INMARSAT study ("Study of Channelization and Routing for Inmarsat 3rd generation Satellite Transponder", Contract INM/218) was awarded in 1987 to Telespazio, aiming at identifying critical technologies for an SS-FDMA on-board router ("IF Processor") able to be utilised for either oceanic coverage (Atlantic, Pacific or Indian Ocean Region, AOR, POR, IOR) with the same repeater architecture.

The study provided an L-band baseline system handling up to about 500 channels 20 kHz spaced, derived by 18 kbps signal information rate + rate 3/4 FEC encoding and Offset-QPSK modulation. The $\pm$ 10° Field Of View (FOV) in the space-to-mobile user link was covered by 18 contoured/spot beams, whose shape is independent of the covered oceanic region and is determined by an RF/IF Beam Forming Network (BFN). The

L-band frequency plan is split into several, different bandwidth frequency slots for interbeam connectivity. 24 slots are allocated to AOR , 19 to IOR and 21 to POR. In total, (24+19+21=) 64 slots are envisaged; their widths span from 20 kHz (1 single channel) to 2180 kHz (109 channels) [1].

Fig.1 shows the principle architecture of the considered MSS repeater. In the C-band forward (outbound) link - a specular configuration characterizes the return (inbound) link -, the (global coverage) feeder link signal is frequency-converted to a convenient IF prior to feed the SS-FDMA router. This consists of an 18-output (=L-band beams) IF Processor, made up by a Filter Bank (FB) and a Channel-to-Beam Allocation (CBA) matrix. An IF/RF BFN - Beam Interpolation (hardwired) matrix + RF Combining Network - synthesizes 18 L-band beams by feeding a 19-horn 3.4-m reflector antenna, High Power Amplification (HPA) being provided by a smaller number of amplifiers.

Reconfigurability requirements of matching different traffic scenarios - i.e. oceanic regions by the same repeater architecture were met utilizing a "switched path filter" arrangement for the IF Processor [3], whereby a 26-way - instead of the theorethical (24+19+21=) 64-way - *fixed* FB is cascaded to a 26x18 CBA matrix. Interbeam connectivity is rearranged by properly activating the matrix cross-points.

The IF Processor specifications (detailed in Table 1) originated a survey of possible technologies, primarily for what concerns FB, which was afterwards designed utilizing a bank of 26 Surface Acoustic Wave (SAW) filters @ IF=30 MHz - 60 kHz minimum 0.5 dB bandwidth instead of the nominally required 20 kHz, definitely beyond the state-of-the-art with the required shape factor, 2.18 MHz maximum bandwidth - having less than 30 kHz 0.5/40 dB transition band.

**TABLE 1. IF PROCESSOR SPECIFICATIONS**

| | |
|---|---|
| FILTERS | - 60-to-2180 kHz bandwidth required<br>- 1 dB peak-to-peak (+-0.5 dB) maximum in-band ripple<br>- 4 degrees peak-to-peak (+-2 degs) maximum in-band deviation from phase linearity<br>- 40 dB minimum out-of-band (sidelobe) rejection<br>- 30 kHz maximum (0.5-40 dB) transition bandwidth, at least for narrowband filters (up to some hundred kHz)<br>- 60 kHz minimum (0.5 dB) bandwidth |
| SWITCH MATRIX | - substantial phase linearity<br>- 50 dB minimum ON-OFF isolation per switch |
| PROGRAMMABLE MIXERS | - capability of mixing with any LO frequency within the comb of 1335 (10 kHz-spaced) components from 6.25 MHz to 19.6 MHz (each beam requires one such CW frequency-per-covered ocean region)<br>- low phase noise |

The very nice frequency response achieved with SAW filters is counterbalanced by the large number of taps (around 5,000) required to assure the steepness of the passband-to-stopband transition (in order to maximize the system spectral efficiency), dictating their physical size to be unusually large, 360 x 38 x 17 mm each packaged filter i.e. 14.2 x 1.5 x 0.7 inches. The overall IF Processor was designed by utilizing current 1 $\mu m$ IC bipolar technology for the CBA switching matrix. The mass and size was 8.3 kg and 40 x 70 x 4 cm, respectively, whereas the power consumption was 10.9 W.

The study, formally completed in 1988, is being integrated by some follow-on activities at the University of Rome and Telespazio, aiming at investigating the possibility of implementing the SS-FDMA router with Digital Signal Processing (DSP) hardware ("Baseband Processor"), utilizing either "multistage" or "block" methods for channel demultiplexing [4]. This would also ease regeneration and *time* switching of channels, implementing *true* on-board processing (OBP) functions and direct-to-user (DTU) operation. Some promising results applicable to mobile satellite systems will be published shortly.

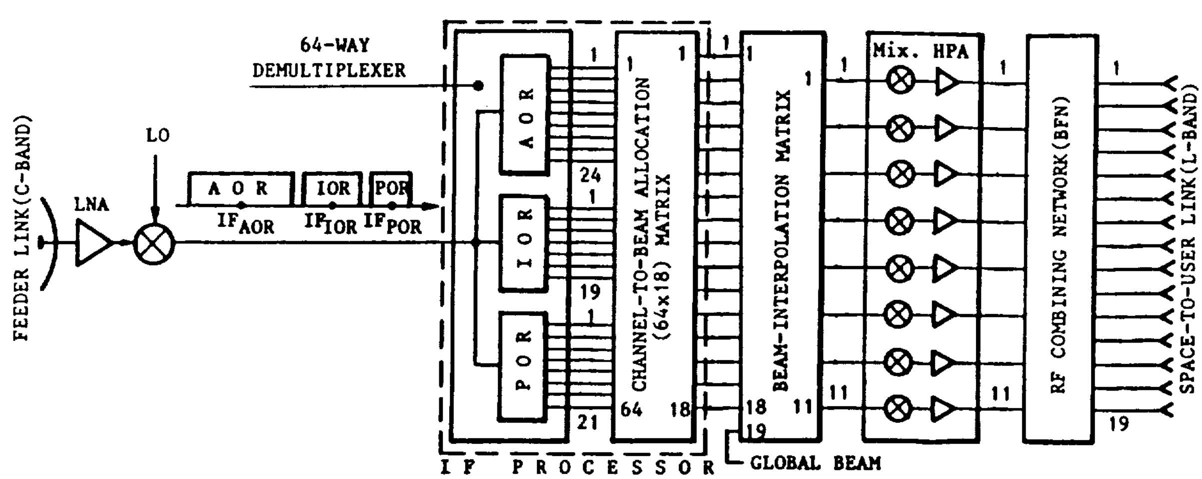


Figure 1. Forward link repeater with 64-way fixed-filter demultiplexing; AOR, IOR, POR are the demux portions selecting the pertinent bands

One interesting alternative to the mentioned architecture is based upon Surface Acoustic Wave (SAW) *chirp* Fourier transform (CFT) processors, that permit to turn the input FDMA channels into output TDM slots [4][5]. Subsequent processing (time-gating and inverse Fourier transform) permits reconfigurable filtering, enabling in principle channel-by-channel routing (not easily achievable by the use of filter banks implemented with any technology).

As a general remark, SS-FDMA is very efficient for what concerns interbeam connectivity, the well known drawbacks caused by non-linear intermodulation effects being at present fairly well balanced by the availability of space-qualified HPA linearizers and (inherently rather linear) Solid State Power Amplifiers (SSPA). Differently from several years ago, a little amount of amplifier back-off is now required (1-2 dB at most), which, together with the off-the-shelf availability of effective FEC codecs for the involved narrowband signals, permit the user terminals to be rather cheap and simple, with no synchronization constraints. On the other hand, although this multiple access technique is inherently "non regenerative" [3], the required on-board technologies are not trivial, and the system performances are substantially interference-limited, differently from the spread-spectrum approach addressed in the next section.

## 3. SPREAD SPECTRUM (CDMA)

Code Division Multiple Access (CDMA) techniques are inherently better suited in interference environments since they exploit spread spectrum peculiarities. "*Averaging*" techniques (e.g. Direct Sequence (DS) spread spectrum) reject (narrowband) interference by averaging them on a wide frequency range; "*avoidance*" methods (e.g. Frequency Hopping, FH) try to avoid that the frequency slots occupied by the useful signal and interference(s) overlap each other. Table 2 summarizes advantages and drawbacks of both techniques. In general, FH is less sensitive to *near-far* problems, although it is less (spectrum) efficient by roughly a factor of 2 than DS. However, this processing gain limitation is overshadowed by the possibility of spreading the signal(s) over much wider bandwidths, which in turn increases the system efficiency [6]. It must be underlined that, whenever bandwidth efficiency is used as a criterion to compare spread srectrum CDMA and SCPC/FDMA systems, the comparison greatly favours the latter (at least in global coverage systems), unless FEC coding is utilized or any peculiar interference-reduction technique is adopted (spot beam coverage, polarization discrimination, voice activation,...[8]). This is because the CDMA system capacity (M user) is limited by co-channel noise (*self* noise), that is the interference contribution by the other (M-1) users. It is evident that any factor that can reduce the self noise contribution results in an increase of spectral efficiency, i.e. a higher number of users can be handled by the system, the overall self noise power density being equivalent to that produced by a lower number of users.

| | ADVANTAGES | DRAWBACKS |
|---|---|---|
| DS | • GOOD ANTIJAMMING PERFORMANCE<br>• DETECTION HARD TO UNAUTHORIZED LISTENER (SECURE COMMUNICATION)<br>• GOOD MULTIPATH DISCRIMINATION | • WIDEBAND CHANNEL WITH LITTLE PHASE DISTORTION<br>• LONG ACQUISITION TIME, OR<br>• HIGH PN CHIP RATE<br>• NEAR-FAR PROBLEM |
| FH | • LARGE SPREADING POSSIBLE<br>• AVOIDING SOME PART(S) OF THE RF SPECTRUM IS POSSIBLE<br>• SHORTER ACQUISITION TIME THAN DS<br>• REDUCED NEAR-FAR SENSITIVITY | • COMPLEX FREQUENCY SYNTHESIZER<br>• ERROR CORRECTION REQUIRED<br>• NON-COHERENT DETECTION GENERALLY TO BE USED |

TABLE 2. DIRECT SEQUENCE (DS) VERSUS FREQUENCY HOPPING (FH) SPREAD SPECTRUM.

CDMA techniques require code synchronization; the possibility of using a kind of network (code) synchronization based on distributing a master code in the forward (outbound) link has demonstrated improved system efficiency, resulting in rather simple and cheap user terminals [9].

An ESA contract to Telespazio ("Space Applications of Frequency Hopping Techniques", ESA/ESTEC Contract 7497/88), started in 1988 and still in progress to build-up a proof-of-concept piece of hardware, aims at assessing the possibility of using CDMA in several environments, including MSSs [10]. The possible utilization of FH as opposed to DS has been investigated and some interesting results derived on the system capacity in the two configurations in comparison with FDMA.

Basically, FH system performances are limited by the possible occurrence of collisions or "hits", resulting whenever the user instantaneous frequency hops on a frequency slot already occupied at that time by another user (packet *erasure*). The data transmitted in that "dwell" interval would then completely lost unless some proper FEC technique is utilised; however, the receiver tolerates a certain amount of (partial) overlapping [11], i.e. is capable of discriminating against partial hits provided that the interfering power (across the received frequency slot) is below a given threshold P (fig.2).

The error probability $P_b$ for a given number of users (M) depends on the probability that, in the event of collision, the foresaid receiver threshold is exceeded. If we assume a spot-beam coverage, the interfering signals coming from different beams have envelopes weighted by the beam pattern, i.e. the related interference (self noise) results lower than in a global beam environment. This means that $P_{b,spot}(M) < P_{b,glob}(M)$, or, equivalently, $P_{b,spot}(M') = P_{b,glob}(M)$, where M'>M: due to the self noise reduction, the system can handle at the same error probability a higher number of users. For the same (self noise reduction) reason, signals transmitted on orthogonal polarizations permit to increase the spectral efficiency; in the case of voice activation

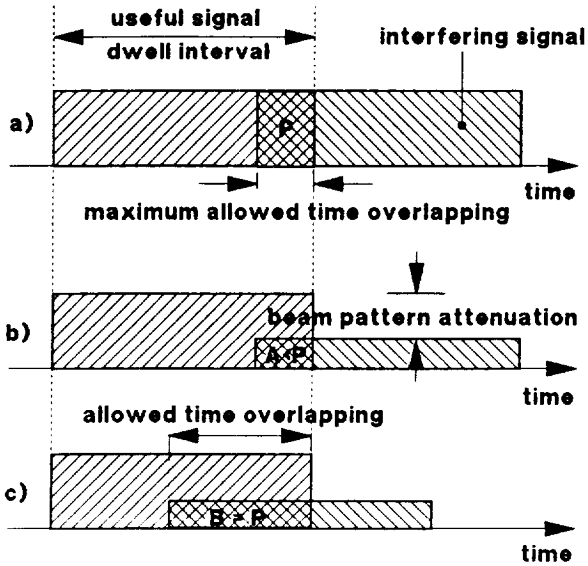


**FIGURE 2.**
**Partial hits between (non-synchronized) users. a)global coverage; b) and c)spot beam coverage.**

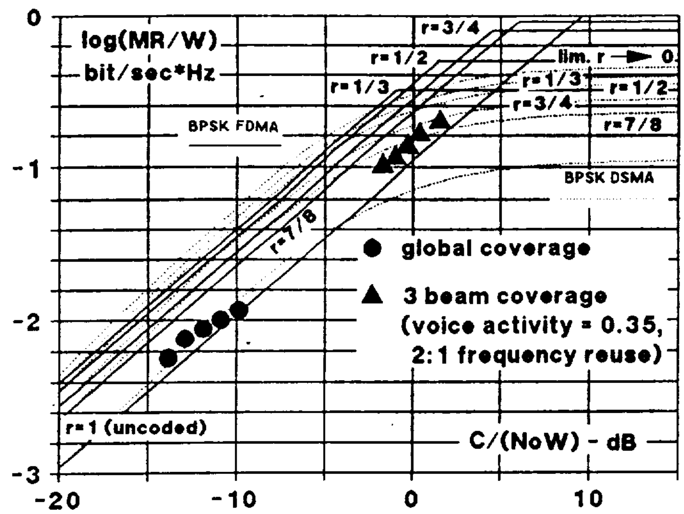


**Fig.3. 16-FSK Slow FH Spectral Efficiency @ BER= $10^{-5}$ versus Carrier-to-Noise Ratio.**

- only pilot tones are transmitted during non-active intervals to maintain synchronization -, the average number of simultaneous users is reduced by roughly a factor of 3 : 1 (=1/activity factor), which reduces the hit probability and, in turn, permits to increase the channel capacity.

For an M-user system, each user transmitting R bit/s in the presence of a rate-r FEC coding with N-FSK modulation, resulting in an individual (frequency bin) bandwidth $W_b$ to be hopped across F slots (overall RF bandwidth $W=FW_b$), the spectral efficiency MR/W can be expressed as $MR/(FW_b) = M\log_2(N)/(FNr)$. On the other hand the carrier-to-noise ratio is given by $C/(N_oW) = (E_b/N_o)R/W$. Hence, for a given number of users (M), level of (FSK) modulations (N), frequency bins (F) and code rate (r), the spectral efficiency MR/W is derived, and the corresponding $E_b/N_o$ (and thus $C/(N_oW)$) value to reach the objective error probability level can be calculated.

Some relevant results are plotted in fig.3 for a 16-FSK (*slow* FH) case - the spectral efficiency has been computed at $P_b=10^{-5}$, although $10^{-3}$ is sufficient in most MSS vocoders -, where some solid and dotted lines are drawn as a reference, indicating the performances of (BPSK) FDMA and DS-CDMA, respectively, in the presence of matched Reed-Solomon codes (rate 1/3-to-7/8). It can be seen that the presence of 3 spot beams, voice activation (gain about 3) and frequency re-use (2:1) by polarization discrimination substantially permits the system to handle about 3x3x2=18 times as many user with respect to absence of those features. However, at least for private user networks, CDMA techniques seem to require extremely large signalling burden to handle a multiple-beam environment, so that the advantages in terms of spectral efficiency should be probably traded-off versus network/system aspects.

FH satellite systems require some (limited) degree of complexity in the user terminals, although at present the development of fast synthesizers made up by Numerically Controlled Oscillators (NCO) permits to employ *fast* FH (several hops-per-symbol), that exhibits attractive system performances. It has to be pointed out, however, that DS spread spectrum techniques have considerably higher maturity than FH in multiple access systems, so that the real applicability of FH-CDMA will depend to a large extent on the technology advances in the years to come.

## 4. FREQUENCY ADDRESSABLE BEAMS

A separate ESA contract ("Study of an Experimental Payload for Ka Multiple Access Services", ESA/ESTEC Contract 7616/88) awarded to Telespazio in 1988 and still in progress concerning follow-on activities on MSSs, substantially aims at investigating the "frequency-addressable" beams concept [12] as applicable to both Data Relay Satellites (DRSs) and MSSs. According to it, a one-to-one relationship does exist between the channel *frequency* and the mobile terminal *location* (fig.4). This is achieved by means of suitable - and in principle simple - BFNs substantially composed by arrays of tapped delay lines (loaded waveguides). The system is designed such as to continuously track the user(s) throughout the motion, by sweeping the carrier frequency across the allocated bandwidth. This causes the necessary band being much wider than in principle required, programmable VCOs being called (at least) on-ground to count for the instantaneous position(=frequency) of the user within FOV. The user terminal is therefore not too simple, although no synchronization problems exist and standard FDMA equipment can be utilized.

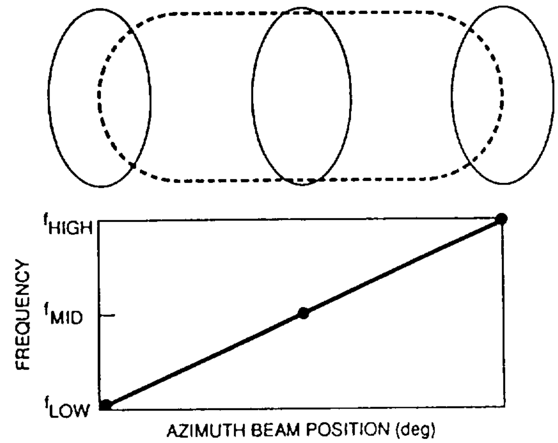


Fig. 4 Frequency address beam arrangement

| PARAMETER | SS-FDMA | FH-CDMA | FAB |
|---|---|---|---|
| Spectral Efficiency | GOOD | GOOD | FAIR |
| (Co-Channel) Interference Rejection | POOR | GOOD | POOR |
| Synchronization requirements | NO | YES | NO |
| Terminal Cost/Size | LOW | LOW-MEDIUM | MEDIUM |
| Space Segment Complexity | MEDIUM | LOW | MEDIUM |
| Flexibility/Reconfigurability | GOOD | FAIR | FAIR |

TABLE 3. SS-FDMA versus FH-CDMA and Frequency Address Beams

## 5. CONCLUSIONS

Table 3 attempts to make a comparison among the three multiple access systems outlined in this paper. SS-FDMA represents maybe a good compromise between flexibility and cost, whilst CDMA is more viable in interference-limited environments. Frequency-addressable beam concepts still require some development efforts to optimize performances.

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