TABLE I
Performance of satellite systems
(GSM full-rate channels)

SYSTEM	A1	A2,B1	B3,C,D	B2	R
DIRECT MS-to-MS COMMUNICATION (N = No, Y = Yes)	N	N,N	N,Y,Y	N	Y
NO.OF SUBSCRIBERS					
1 beam	12888				
7 spot beams		24045	24045	8729	33885
12 spot beams		41220	41220		56475
MS PEAK POWER (W)					
1 beam	60				
7 spot beams		6	6	6	6
12 spot beams		3	3	3	3
SPEECH DELAY (ms)	440	440	350	350	350

5. Discussion on critical issues of the integrated system

In principle satellite resources (in terms of both radio channels and network entities) could be considered fully equivalent to GSM resources: this is the approach followed in obtaining the previous results, that indicate a small subscriber capacity for the satellite network compared with the GSM network. Differently, the satellite may play a special role in the integrated context, as explained in the following.

Starting from the basic concept that satellite channels can be shared among the much larger user community of a satellite spot beam, system integration will allow customers to access both the satellite and the GSM network transparently but the channel choice will not be based only on link quality but on more advanced network criteria, aiming at achieving a higher system efficiency and taking advantage as much as possible from the presence of satellite channels.

5.1 *Criteria for resource assignment*

If satellite must have a distinct role from the cellular network, call handling criteria for assigning the radio channels to the requesting users must not be based only on the quality of the signal received by the mobile terminal: link quality is certainly the most natural decision element, but it does not discriminate between channel costs and the achievable network efficiency. In the GSM network link quality is appropriate because only "cellular" channels are involved; nevertheless, the second generation GSM already includes procedures, like traffic handover, that are network based. This demonstrates that the GSM network is already evolving towards a more efficient channel usage.

Clearly, satellite channels will be automatically chosen in those regions where the GSM system is not available and this is a well known element that boosts the presence of a satellite. It applies to regions outside the edge of GSM coverage but still interesting to European users and also to such areas (rural, Eastern Europe) for which coverage is scheduled only in the long run. Also areas that are temporarily left without GSM service, owing to failures of one or more Base Stations, would take advantage from available satellite channels. This makes it absolutely necessary to allow a direct mobile-satellite access from the call set up phase and not only for transmission of traffic data; furthermore, in the areas not covered by the GSM network, the signalling messages (paging, handover, call request etc.) are also handled by the satellite network.

Efficiency considerations suggest to assign traffic channels in a different way where satellite and cellular coverage overlap, taking into account that:

a) satellite channels are more costly and

b) they can be shared by a much higher mobile community (one spot beam includes hundreds of terrestrial cells). This motivates the proposal of assigning satellite channels only after verification that GSM channels are unavailable (for whatever reason) to the incoming call.

The proposal, to be elaborated and refined, is that, mobile terminals will always access the GSM network (where available) on GSM carriers, switching to the satellite carriers only if a congestion of the GSM carriers in the cell is encountered. This functional choice does not seem to imply substantial changes to the software design of GSM Network Elements since it should be entirely handled by the mobile terminal.

The proposed channel assignment strategy allows to take advantage entirely of the intrinsic flexibility that is a powerful feature of satellite systems. For example, the GSM network is rather vulnerable to local overloads: it is recalled that carrier reconfiguration procedures are included in the GSM design but the involved complexity suggested to defer implementation after Phase I. Satellite channels, on the contrary, can be easily dedicated to areas temporarily overloaded by unexpected events. This is clearly possible only if channel assignment obeys to network status criteria. In this way, the satellite contributes to level blocking probability and the whole network behaves more properly.

A non negligible advantage of an integrated cellular/satellite network produces an increase of the useful life of the GSM system; here, useful means that the offered service respects a preassigned quality for an increased value of offered traffic, i.e. customers, than expected in the initial dimensioning phase. Hence, the only existence of integrated satellite resources represents an economy factor in the evolution of the GSM network. A further, non negligible, increase in the acceptable number of subscribers (the quality threshold being equal) can be achieved with a careful resource management, as proposed in this subsection.

PLMN operators should look favorably at this approach in that allows to follow the customers increase satisfactorily with a more gradual less expensive) program of investments.

5.2 *Internetwork procedures between cellular network and satellite network*

The identified critical functions to be accomplished by the integrated system are analyzed in the following.

5.2.1 *Location of mobiles*

In the GSM network, the location of mobiles (registration and paging) is achieved by the cooperation of the HLR, VLRs and MSCs. Similarly, the location of mobiles in the integrated network can be accomplished by the cooperation of the HLR, the VLRs and the satellite network. In this respect, the beam in which the mobile is located corresponds to the Location Area controlled by an MSC. The satellite FESs act as the MSCs and the VLR has to register which FES (conceptually, which "satellite" MSC) controls the MS.

As indicated in [1], the main problem is to define which FES has to control the MS: the solution depends on the selected satellite configuration.

5.2.2 *Call handling*

Several cases will be distinguished i.e. MS originating call to fixed users, MS originating call to MS and MS terminating calls. Direct MS-to- MS connections by the satellite network with a single hop are possible only for a satellite with on-board switching [1]. A key point is checking the practical applicability of the GSM signalling procedure to the satellite network, where the main difference between the two networks is the signal propagation delay.

5.2.3 *Handover*

In a classical approach, handover between the satellite and the GSM networks should basically take place whenever during a call the MS measurements indicate that the alternative network offers a better link than the one currently in use. Alternative and more efficient handover decisions should be essentially network based and oriented to maintain a very high availability of those channels that exhibit the highest sharing level, i.e. satellite channels. Consequently, the "Satellite→GSM" handovers facility could be an interesting area of investigation.

On the edge of GSM coverage the availability of "GSM→ Satellite" handovers would improve the integrated network performance avoiding forced disconnections due to the fact that the mobile terminal is leaving the GSM network but still remains under the satellite coverage. However this kind of handover would be based on link quality measurements that in the current design of the GSM network are handled by the BSS and the MSC. The introduction of such a facility would request modifications not limited to the mobile terminal and this is an undesired feature.

On the other hand, the described GSM→Satellite handover should concern a small percentage (i.e. those in a conversation state) of the mobiles that are leaving the GSM coverage and, although attractive, such a facility is not believed to be essential. In any case, should a forced disconnection occur, access to the satellite network can be attempted automatically afterwards. A similar situation is encountered currently for calls in progress when the border between two PLMNs is crossed.

A careful definition of handover procedures is imposed by the existence of severe synchronisation problems between the two networks. A solution for Satellite-GSM handovers that seems promising and worth being analyzed could be the following one: to consider the handover request, coming from the FES, as a normal call directed to the MSC controlling the involved MS. This implies checking with attention compatibility with the existing GSM procedures.

If the convenience of handovers from Satellite to GSM is verified, the subsequent step must be the definition of appropriate procedures for both the mobile terminal and the connection establishment in the fixed network.

5.2.4 *Synchronisation strategy*

For the synchronisation strategy of the TDMA access, in both the GSM and the satellite network, two states (modes of operation) are distinguished:

(i) normal state, which exists during a call in progress;
(ii) access state, which exists in the call set-up phase, e.g. at the start of a new connection or at handover.

i) Normal state

In the GSM normal operation, the BSS continuously monitors the delay from the MS and, when the delay increases significantly, communicates the variation to the MS, which updates its transmission time. In this way, the burst transmitted by an MS is always correctly positioned and a guard time of about 30 ms is sufficient for any cell size.

The same procedure can be applied to a satellite system, performing the measurements on board or at an earth station. Therefore no change in the GSM synchronisation procedure is necessary in this state. The main difference comes from the longer propagation delay, that must be taken into consideration in the analysis.

ii) Access state

In the GSM access state, the MS sends an access burst of 88 bits (0.325 ms) with a guard time of 68.25 bits (0.252 ms). In this state the MS has no information on its position with relation to the BSS, but the guard time is sufficient to allow for a cell radius of about 35 km and one slot is sufficient even in the access state.

A different situation arises for satellite with one beam or multiple spot beams. Let us consider the more interesting case of multiple spot beams with a spot radius that can be of about 1000 km. A guard time of 7.2 ms is therefore necessary, corresponding to 1950 bits. Of course, in this case, one slot is not enough and even one frame (4.615 ms) is shorter than the necessary guard time: therefore a different approach is required.

Two alternatives are possible:

(A) Carrier reservation for the access state.

A complete carrier is reserved for the access procedure in the satellite network for each spot (access carrier). This access carrier is subdivided into access-time slots corresponding to two GSM frames, the duration of which (9.23 ms) is sufficient to accommodate the necessary guard time and the access burst duration. The access-time slots are simply derived by the MS terminal from the received timing signals from the satellite, for example detecting the start of even (or odd) frames. Successively, the satellite system receiving the access burst measures (on board or at an earth station) the estimated round-trip delay (satellite/MS/satellite) and sends the corresponding timing-advance information to the MS, which can thus start using the burst format of the GSM system. Unslotted ALOHA appears to be an appropriate solution.

As shown in [1], the carrier reservation solution for the synchronisation is able to support more than 800,000 subscribers with an average transmission time of approximately 325 ms (on board measurement) or 650 ms (ground measurement).

(B) Co-operation with a positioning system.

If an autonomous positioning system (such as the Global Positioning System) is available at the MS, the mobile position could be known with a sufficient accuracy (i.e. well within a radius of about 35 km) to permit the use of the same GSM procedure in the access state. The impact on terminal complexity will be duly addressed, including the additional units required to process the data received from the Positioning System.

5.2.5 *Staggering of transmission and reception phase at the MS*

In the GSM network, the staggering of the transmission and reception phases at the MS avoids the use of a diplexer. In the satellite network, with much wider spot beams than the cells are, when the mobile is roaming during the call, the same staggering does not necessarily avoid the use of a diplexer.

Consequently, the GSM procedure must be carefully checked during the study or an alternative staggering procedure has to be defined for the satellite network. If such alternative staggering is not achieved, the limited cost and weight of a diplexer are not a critical factor for its insertion in the mobile terminal provided that link budget supports it.

6. Conclusions

The complete integration of an LMSS in the terrestrial cellular network is a challenging system architecture that requires solving problems at both transmission and network level. However the potential advantages of the integrated system suggest to carefully study the appropriate solutions.

The main technical advantages are:

- only one mobile terminal is required for both the satellite and the GSM systems, making it attractive for its potential low cost;
- the FESs of the satellite system are similar to the GSM BSS and MSC switching centres: this avoids an expensive development for the FESs that can be adapted from the GSM BSS and MSC stations and may even be collocated with some of them reusing the common parts.

The main operational benefits that could be achieved are the extension of the mobile services (bearer services, teleservices, supplementary services) offered by the GSM system to:

- not yet covered Western Europe areas;
- Eastern Europe and North Africa areas;
- aeronautical and maritime mobiles, so that one integrated land/aeronautical/maritime system could be conceived for all mobiles.

In particular, architectures A2, Bl and B3 allow for a quick deployment of a transparent satellite payload: these solutions have some limitations and drawbacks and a reallocation strategy is more difficult to implement. Nevertheless they provide a feasible system with a sufficient capacity for the start-up phase.

Architectures C and D are much more efficient, avoiding all the limitations and drawbacks of the previous solutions at the expense of a more complex on board payload. Their adoption would be more easily justified for an increased number of spot beams and higher frequency bands (instead of L band): the consequent increase of the system capacity in terms of total number of available channels would justify the additional design cost.

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Appendix

This appendix presents very preliminary link budgets intended to highlight the feasibility of the GSM satellite link considering the European Mobile Satellite (EMS) and the L-band Land Mobile (LLM) payloads.

The main assumptions of the budgets and their rationales are the following:

- the FESs are provided with a 4.5 diameter antenna, with an EIRP per carrier equal to 61 dBW and a G/T equal to 28.6 dB/K. With such values, the forward uplink C/No and the return downlink C/No are remarkably higher than the required C/No: so the corresponding links can be neglected in the link budget evaluations;
- the MS has an electronically (or mechanically) steerable antenna with a transmitting gain of to 12 dB and a G/T equal to -12 dB/K;
- the EMS payload is a transparent single beam payload covering Europe. Its total EIRP is 44 dBW and 32 dBW for the forward payload and the return payload respectively; its Ku-band G/T and L-band G/T are -1.4 dB/K and -1.5 dB/K, respectively. The LLM is a transparent payload covering Europe with a spot beam configuration at L-band and a single beam at Ku band; its total EIRP is Sl dBW and 38 dBW for the forward payload and the return payload, respectively; its Ku band G/T and L-band G/T are -1.4 dB/K and 2.5 dB/K, respectively;
- the fading environment which has been considered is a rural/suburban environment. Fading has been analysed by conceptually separating a ''shadowing effect'' which takes into account the phenomena affecting in the same

TABLE A1
Forward link budget

UPLINK C/N0 (dB Hz)	76.2
SATELLITE EIRP PER CARRIER (dBW)	34.3
DOWNLINK PATH LOSS (dB)	-188
MOBILE G/T (dB/K)	-12
ATMOSPHERIC LOSS (dB)	-0.5
BOLTZMAN (dBW/K)	228.6
SHADOWING MARGIN (dB)	- 3
DOWLINK C/N_0 (dB Hz)	59.4
BIT RATE (dB)	54.3
REQUIRED E_b/N_0 (INCLUDING MULTIPATH) (dB Hz)	3
IMPLEMENTATION MARGIN (dB)	2
OVERALL C/N0 (dB Hz)	59.3

TABLE A2
Return link budget

MOBILE POWER PER CARRIER	14.1 (EMS); 10.2 (LLM)
MOBILE ANTENNA GAIN (DB)	12
MOBILE POWER LOSS (dB W)	-0.8
POINTING ERROR (dB)	-0.2
UPLINK PATH LOSS (dB)	-189
SATELLITE G/T (dB/K)	-1.5 (EMS); 2.5 (LLM)
ATMOSPHERIC LOSS (dB/K)	-0.5
BOLTZMAN (dBW/K)	228.6
SHADOWING MARGIN (dB)	- 3
UPLINK BUDGET (dB Hz)	59.77 (EMS); 59.8 (LLM)
DOWNLINK BUDGET (dB Hz)	69.6 (EMS); 68.6 (LLM)
BIT RATE (dB)	54.3
REQUIRED E_b/N_0 (INCLUDING MULTIPATH) (dB Hz)	3
IMPLEMENTATION MARGIN (dB)	2
OVERALL C/N_0	59.3

way the direct and the multipath signal (a 3 dB shadowing margin has been taken) and a "multipath effect" which has been characterized through a ratio between the direct signal power and the multipath signal power equal to 10 dB (preliminary simulations related to a full rate GSM voice channel, have shown that, with the aforesaid multipath, an Eb/No equal to 3 dB is necessary)to satisfy the GSM quality requirements.

The main conclusion coming out from the budgets are the following:

- from the forward link budget (Table Al) it results that a satellite EIRP per carrier equal to 34.3 dBW is necessary . This means that, without considering voice activation, the EMS and the LLM payload can support 9 and 46 GSM carriers respectively (the number of traffic channels is obtained multiplying the above figures by 8 and 16 for the full-rate GSM and half-rate GSM, respectively);
- from the return link budget (Table A2), a peak mobile terminal power equal to 25.7 W and 10.5 W results necessary for the EMS and LLM cases, respectively. Solid state amplifiers can supply the above-mentioned powers; for such amplifiers the complexity (and costs) is related to the mean supplied power. In that respect, it should be noted that the mean necessary power is 1/8 (full rate GSM) or 1/16 (half rate GSM) of the peak power.

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