Issues for the integration of satellite and terrestrial cellular networks for mobile communications

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Satellite and terrestrial cellular systems naturally complement each other for land mobile communications, even though the present systems have been developed independently. The main advantages of the integrated system are a faster wide area coverage, a better management of traffic overload, an extension to geographical areas not covered by the terrestrial network and, in perspective, the provision of only one integrated system for all mobile communications (Land/Aeronautical/Maritime). To achieve these goals, as far as possible the same protocols of the terrestrial network should be used also for the satellite network. This paper discusses the main issues arising from the requirements of the integrated system, illustrates some preliminary results and presents possible improvements for the technical solutions.

1. Introduction

Mobile, in particular land mobile, communications are expected to be the fastest growing sector of the European telecommunications market in the near future.

The increasing demand of mobile communication services is boosting Administrations and industries to develop and design systems able to satisfy the requirements of different users communities. A lot of research activities are being undertaken and different mobile systems are being defined for both terrestrial cellular and satellite networks.

In this scenario, which is far from being completely defined, a Mobile Satellite System (MSS) has an important role in both a global and regional environment. As a matter of fact, its deployment allows full design capability to be immediately available to the entire coverage area. This is not possible for terrestrial networks which need expanding over several years until the objective is reached. Moreover, a satellite can even more easily cover all those areas with limited commercial importance where a cellular network is unlikely to be ever implemented.

In addition, satellites are intrinsically characterized by a flexible resources assignment, particularly useful where mobility introduces another element of randomness to the offered traffic. Hence, it is possible to reconfigure (also temporarily) the satellite channels allocation, to cope with sudden overload situations in the coverage area. This feature is more useful when the payload antenna generates a spot- beam coverage and the transponder provides on-board processing and routing capabilities.

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At present, terrestrial and satellite systems are independently developed. No effort has been spent to integrate the two systems although an integrated system would take advantage of the peculiarity of each system and provide better service to the covered area: it is thus interesting to investigate the possibility to integrate a Mobile Satellite System with a terrestrial cellular system. For Europe, in particular, it is worth analysing and studying the integration of a European Land Mobile Satellite System and the pan-European cellular GSM network.

Early in the nineties, the pan-European GSM cellular mobile system will start to be operational: it is based only on terrestrial infrastructure, with an expected steady-state number of mobile subscribers in the order of 15 millions. The coverage of the terrestrial system, however, will be limited to densely populated areas, airports and main connection routes for several years after. Even in the long run it may be not convenient to extend the terrestrial system where traffic is very low or to particular geographic areas outside Western Europe (e.g. Eastern Europe, Middle East, North Africa) and to other users (e.g. maritime and aeronautical). Furthermore part of the land mobile traffic (e.g. peak traffic, special services traffic) may not be optimally carried by the cellular network or may imply such a considerable risk that the investments are not compensated for by the actual revenues obtained from an extremely variable traffic.

A satellite system will effectively complement the terrestrial cellular network. The key of success of such a complement is in the ability to achieve a high level of integration between the two systems and in particular to operate with the same mobile terminal.

The main issues to be addressed for this goal are:

- Analysis of the most integrated architectures, highlighting signalling protocols, their performance and the possible impact on mobile terminals. The required modifications to the cellular system should preferably impact on mobile terminals rather than on the terrestrial networks.

- Definition of the specific procedures for location of mobiles, call handling, handover, synchronization, staggering between transmission and reception.
- Definition of the radio section, with focus on the analysis of the satellite radio link.

Depending on the availability of technical solutions and the onboard satellite architecture (transparent, regenerative), different degrees of integration between the satellite and the terrestrial cellular systems can be envisaged, leading to different operational capabilities.

2. Cellular system main features

The Groupe Special Mobile (GSM) was established in 1982 to formulate the specifications for a Pan-European mobile cellular radio system providing users with automatic roaming over all Countries of Western Europe and allowing both fixed to mobile (and reverse) and mobile to mobile connections. A wide variety of bearer services, teleservices and supplementary services has been considered from the early specification phase and included in the standard.

The new system aimed at enhancing spectrum efficiency (i.e. higher amount of customers) of the existing analogue mobile networks, as well as transmission quality and service variety . The availability of new technologies and of digital techniques more suitable to speech and channel coding seemed promising for service integration between voice and data. Furthermore, the lower sensitivity to interferences of digital signals allowed to reuse frequencies at a much smaller distance with a consistent radio channels capacity increase.

The GSM system will become gradually operational starting from early nineties; initially it will be available only in the most important European towns, with a coverage extension to airports and major motorways. The full European coverage will be reached after several years from system activation, even if a rapid growth is expected as it happened for the analogue mobile systems.

Both functional entities and interfaces of the GSM system have been specified. In particular the definition of interfaces has been developed in detail to ensure full interworking among the national GSM networks and compatibility between network elements supplied by different manufacturers, at least for the accomplishment of telecommunication functions.

The main building blocks of the GSM system, as indicated in Fig. 1, are [1]:

- the Mobile Station (MS);
- the Base Station System (BSS), connected with the MS through a radio link; a BSS controls one or more cells;
- the Mobile-services Switching Centre (MSC), to which the BSSs are connected through a terrestrial link; the MSC is the interface between the fixed terrestrial network and the GSM network.

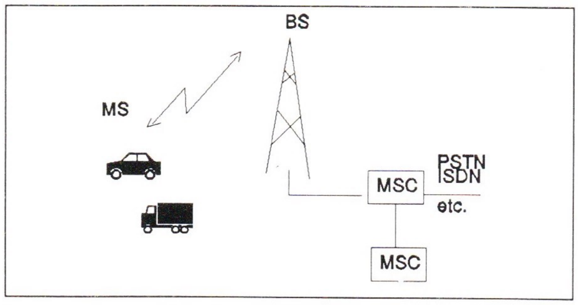

Fig. 1 - GSM main building blocks.

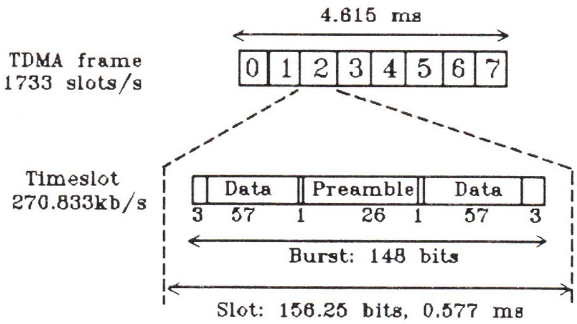

Fig. 2 - Basic format of the GSM TDMA frame.

The main specifications proposed for the GSM system are the following:

- Digital transmission;
- Frequency bandwidths: 25+25 MHz (890-915 and 935-960 MHz bands);
- Carrier spacing: 200 kHz, providing 125 available carriers in 25 MHz bandwidth;
- Frequency reuse: 9 groups of carriers for the cellular operation;
- Multiple access: TDMA with 8 full rate channels per carrier with the basic format shown in Fig. 2.
- Cells of radius up to 35 Km.

Two other functional entities of the GSM system are:

HLR: the Home Location Register, where all Mobile Stations served by the same PLMN Operator are registered. It contains the subscriber profile and the location information for all registered Mobile Stations: the location information consists in a Roaming Number, used for routing the call to/from the mobile, located at the time of the call. At least one HLR must be present in each country;

VLR: the Visited Location Register, which controls a geographical area (i.e. a number of cells) and contains the subscriber parameters and location informations for all the Mobile Stations currently located in that area; every Mobile Station is registered in a VLR and in its HLR. Automatic roaming is made possible by the combination of the HLR and VLR location informations.

The MSC performs all the switching functions required for the management (set up, disconnection, handover, etc.) of the call to/from the MS. The MSC does not contain the subscriber parameters and interrogates the location registers. Several MSCs may share the same VLR or the MSC and VLR may be fully integrated, thus allowing flexible network designs of the location of MSCs, VLRs and HLRs.

The correct operation of the GSM system requires an information exchange between all functional entities both during a call to/from a mobile and the periods when the mobile is idle. The GSM network, and in particular the HLR and the VLR, must keep track of the location of each mobile both when it is idle and when a call is in progress; in the latter case also a dynamic routing of the call in progress must be implemented to connect the mobile going from a cell to another or from a VLR area to another (handover). All the signalling informations related to these functionalities have been specified accordingly as close as possible to the CCITT Signalling System No. 7 (GSM Rec. 03.04).

For the signalling and routing operations required to connect the MS wherever it is, the GSM system is organized in hierarchical geographical areas. The smallest area is the cell, which is the area where the MS communicates by a specified set of frequencies via the same antenna system in the BSS. The BSS area is the area covered by a BSS and is equivalent to the cell when omnidirectional antennas are used; however, a BSS can support more cells with an assigned, nonoverlapped set of frequencies. The location Area is the area in which the mobile can move without informing the location registers of its movement. If the mobile moves into another location area, the location registers are updated. The MSC area is the area covered by one MSC. In a country (or network) there may be one or more MSCs.

The MS is identified by an international mobile number and its movements from one location area to another are communicated by the VLR back to the HLR, which maintains and updates the MS and the MS location.

The automatic handover is one of the key features of the GSM system (as far the other cellular networks), to allow MS roaming during a call in progress. The GSM recommendations specify the procedures to be followed to implement handover. Mainly it is based on the link quality of adjacent cells measured by the MS and reported to the network, that has to set up a new connection to the MS and to switch to it at the appropriate time instant without any significant communication interruption.

The handover procedures are different depending on the involved cell types. In increasing order of complexity the handover procedures are:

- between channels of the same cell
- between cells of the same BSS
- between cells of the same MSC area
- between cells of different MSC areas.

Presently the recommendations do not specify handover between different Public Land Mobile Networks (PLMN).

3. Integration scenarios between cellular and satellite networks

To date, terrestrial and satellite land mobile systems have been separately developed and tailored to the environment where each system operates. Due to the different radio characteristics (signal attenuation, propagation delay, multipath channel characteristics, etc.), it seems, at first glance, that the integration of the two systems is quite hard to be achieved. Nevertheless, recent studies focused preliminarily on the possibility of integrating the terrestrial GSM network with a Land Mobile Satellite System (LMSS) and have concluded that the integration is feasible (although different technical solutions have been envisaged) [1, 2].

The integration between the GSM network and a LMSS is quite attractive since:

- the integrated system allows to set-up quickly a mobile communication service in all Europe. The European coverage of the GSM network will not be soon available and it will be certainly reached through intermediate steps. The complete European coverage might not be achieved by GSM: the less populated areas could be excluded if the offered traffic is not high enough to justify the investment for a BSS.
- the integrated system allows to cover the Eastern Europe, the Middle East and North Africa where the GSM is not implemented and mobile services can be offered via satellite.

The present opening of the Eastern Countries and the development of the Mediterranean countries is expected to increase the commercial interchanges between Europe and these countries along with the needs for mobile communications. Consequently, the deployment of an integrated system will be a real and challenging business opportunity.

- the increase rate of the number of GSM customers is likely to be very high and will be necessarily limited by the evolutionary growth of GSM infrastructures. Quality of service figures, like call refusal probability, heavily depend on the amount of available radio channels and will be a natural control to the users growth towards the long term forecasts. An operational compatible/integrated LMSS is capable of raising service quality in the transient phase of the GSM network deployment or of satisfying more customers at a preassigned quality level.

3.1 *Integration levels*

It has been shown [3] that several levels of integration between the GSM and LMSS are possible. In the following classification each level includes the functions of the previous one.

- Geographical integration. The two networks, still separate, complement each other over a wider geographical area. They are independently conceived and basically aim at supplying different services to two disjoint groups of customers.
- GSM services (or a sub-set) integration. The two networks are still distinct and may be based on different techniques. Nevertheless, at this level, the local terminals, supporting the desired service, can be employed independently of the selected terrestrial or satellite link. This can be achieved by appropriate protocol conversions.

- Network integration. The two systems have common network infrastructures. The fixed user requests connection without deciding the call routing (cellular or satellite). In this approach, the satellite systems can still be based on techniques and system parameters optimized for satellite applications.
- Equipment integration. This approach is architecturally equivalent to that of the previous level, with the main difference that the techniques of the satellite system (access parameters, bit rates, protocols, etc.) are as close as possible to those of the cellular system. This aims at simplifying the dual-mode terminal implementation. The common core of the terminal logic, baseband and possibly modulation equipment) can be utilized for both terrestrial and satellite operating modes. Furthermore, it is possible to reuse for FES (Fixed Earth Stations) of the LMSS equipment closely derived from the BSS and MSC.
- System integration. This solution represents the maximum conceivable level of integration of the satellite network with the GSM, in the sense that the coverage area provided by the LMSS is regarded as one (or more) cells of the GSM system. This solution includes very advanced system features such as the handover of a live call between satellite and terrestrial cells, whenever link quality, channel occupancy or another performance criterion makes it necessary.

3.2 *Critical areas for GSM/LMSS integration*

The previous paragraph has summarized all possible levels of integration between a cellular network and a Land Mobile Satellite Network. The lowest levels, in reality, do not represent an integration of the two systems but rather, they depict levels of co-existence of the two systems. Consequently, the considerations reported in this paragraph refer to major problems arising when the highest level of integration, that is the system integration, is to be achieved. The most critical areas identified so far are briefly summarized.

Firstly, the handover problem. The definition of an integrated system involves the definition of the handover procedures between the two networks, i.e. a very complex feature due to the inherent transmission delay of LMSS (round trip delay) and the resulting real time delay adjustments of the GSM frame. Consequently, effort need to be spent to investigate complexity and convenience of such procedures.

Secondly, the random access and synchronization protocol. When the MS accesses the GSM system, it transmits a short burst with a guard time dimensioned to allow accessing the frame without any knowledge of its distance from the BSS in a cell of 35 Km radius. In a satellite system the same guard time cannot accommodate the range of distances between mobile terminals and satellite; therefore the mobile random access procedure must be modified or the mobile must be equipped with a positioning system.

Thirdly, the propagation environment. The modelling of the satellite and GSM channels are different with different effects of multipath and shadowing. Then, appropriate countermeasures could be necessary for the satellite link.

Fourthly, the network and mobile terminal integration. In general, the integration of two systems involves the revision of procedures and protocols. In this particular case, to propose a successful integrated system, it is mandatory to find integration solutions that imply no real changes to the existing network equipment (in particular the MSCs), since the GSM network will be already implemented when the satellite system should be introduced (anyhow the network elements would have already be designed and developed). Possible changes may be in the area of the mobile terminals (to be anyhow modified at both radiofrequency and base-band level, for compatibility reasons).

Finally, the staggering of the transmission and reception phases. The mobile terminal of the GSM system is not provided with a diplexer since the reception and transmission phases are staggered of three slots of the GSM TDMA frame. In the satellite system spots dimension and propagation delay make the same staggering insufficient to avoid the use of a diplexer and therefore an appropriate staggering procedure shall be studied in connection with the TDMA initial synchronization procedure.

3.3 *Access technique*

As to the satellite access technique identification, the solution which better meets the integration requirements with the cellular network is TDM in the forward link (from the Fixed Earth Stations (FESs) to the Mobile Stations (MSs)) and TDMA in the return link (from the MSs to the FESs), since it allows to exploit the existing equipment in the MS. Ideally, only the RF part of the GSM MSs should be adapted and properly equipped in order to be compatible with a satellite environment.

The return link budget is definitely the basic problem which could prevent from implementing the TDMA on the return link and, consequently, from reusing the GSM format. In particular, one link budget parameter to be carefully assessed is the fade margin: in order to meet the return link budget, it might be necessary to provide the FESs with receivers able to exploit both the direct and the reflected paths (as for the GSM BSSs), if viable in a satellite link.

3.4 *Satellite configurations*

Three different scenarios can be envisaged for the on-board architecture of a satellite system integrated with the terrestrial GSM network: transparent satellite, satellite with limited on board processing and satellite with enhanced on board processing.

3.4.1 *Transparent satellite*

A number of different network architectures can be envisaged, all assuming a single beam for the Fixed Earth Stations (FESs) [2].

A1 - Only one FES for the whole system; a single beam for mobiles. A2 - Only one FES; multiple spot beams for mobiles.

In both solutions the FES is the unique interface with the terrestrial GSM network: all satellite traffic to/from mobiles passes through this station, whose role is similar to a GSM Base Station, with its associated MSC, that now controls spot beams instead of cells. The very long terrestrial tails from the FES to the fixed end users might not be acceptable for the management problems associated with the presence of different Administrations in Europe. In addition, solution Al can provide a limited capacity.

Bl - Multiple FESs in the single beam (e.g. as many as the number of spots for mobiles); multiple spot beams for mobiles. This solution assumes that the traffic directed to mobiles of a given spot passes through the FES located in (or closest to) that spot. The satellite simply connects a MS with its closest FES, which again performs the functions of a GSM BSS now controlling only one spot. Long terrestrial tails are still present but only for traffic directed outside the spot of the MS, a situation that, due to the traffic distribution [2], is unlikely to occur.

B2 - Multiple FESs; multiple spot beams for mobiles. To reduce the terrestrial tails the mobiles could be connected to the FES closest to the end user. To simplify the constraints on the synchronization procedure among all the FESs accessing the satellite, a fixed number of TDMA carriers can be assigned to each combination of FES-spot. This fixed assignment may lead to an inefficient system if a small number of satellite carriers is available.

B3 - Multiple FESs; multiple spot beams for mobiles. The inefficiency of solution B2 can be eliminated using an unconstrained TDMA access from FES to MS: this however increases the complexity of the FES [2].

In any of the above configurations a transparent satellite alternative substitutes the GSM network link MS-BSS-MSC with the satellite link MS-Satellite-FES. All the network functions remain under the responsibility of the terrestrial GSM network. The transparent satellite allows for the communication with mobiles in areas covered by the satellite and not by the GSM network, but, it cannot be used for direct MS-to-MS communication via satellite.

3.4.2 *Satellite with on board processing*

Two alternatives can be considered:

C - In addition to multiple FESs and multiple spot beams for mobiles, a satellite with a base-band on board processing, capable of switching the calls can be assuming. All the functions required for call routing and system management can be provided on ground at a control center through a double-hop connection.

The uplinks and downlinks between the satellite and the MSs are in TDMA and, respectively, in TDM on multiple carriers, as for the GSM system. The uplinks (downlinks) between the satellite and the fixed FESs are in TDMA (TDM) on a high-rate unique carrier. The on board switching function provides for interconnections between the link on the FES side and on the MS side. This technical solution simplifies the complexity of the FES, provides end-to-end connections with relatively short terrestrial tails and allows for direct MS-to-MS communications through the satellite. Moreover a reallocation of resources (channels) among the various FESs to improve the system efficiency is now possible through the ground control station and it is very easy to increase the number of fixed FESs as required.

D - With respect to C, this solution adds other processing capabilities on board in order to avoid the double-hop connection for some signalling functions required by the integrated system. This is of course the most powerful system with optimized performances. At the moment it can be considered as a long term solution, whose feasibility and convenience will depend on the improvements of the on board processing technology and the integrated system operational requirements.

4. **Satellite system performance**

The performance of an integrated system is considered referring to the present bandwidth allocation for a land mobile satellite system. The different alternatives described in Sect. 3 are compared with the following assumptions:
- Bandwidth: 7 MHz (full duplex) at L band;
- Carrier spacing: 200 kHz
- Beam configurations: Eurobeam, 7 spot beams, 12 spot beams
- Frequency reuse (spot beams cases): 3 groups of carriers
- Multiple access: TDMA with 8 channels per carrier, with the same format as the GSM system;
- Subscriber traffic intensity: 20 mErl/sub.
- The system capacity is assumed to be limited only by the number of available channels to/from mobiles: in other words the link to/from the FESs is assumed to have the necessary bandwidth (operating at Ka or Ku band) and a full connectivity is assumed on board the satellite.

Table I shows the performance of each satellite configuration. Greater details are reported in [1]. The number of subscribers refers to a blocking probability (grade of service) of 2%, according to the Erlang-B formula. The last column (system R) gives the maximum system capacity when bandwidth reallocation among the spot beams for mobiles is employed: the result refers to the limiting case of maximum reallocation of the available channels. The result for alternative B2 has been obtained assuming a traffic distribution of 95 % in the same spot and 5% uniformly distributed among the other spots [4]. Link budgets for different satellite systems are reported in the Appendix.

Peak power indicates the RF power required at the MS during the burst transmission in the TDMA frame. The mean RF power required at the mobile transmitter is therefore approximately 1/8 of the peak power. In case of half-rate channels the mean power is further halved and the system capacity doubles.

CCITT Recommendation G.114 suggests a maximum delay for speech of 400ms.

GSM Recommendations assume a delay of approximately 90ms for the speech transmission between the MS and the BSS (or the MSC), including signal processing and transmission. With 260ms of signal delay through the satellite, CCITT Recommendation can bc satisfied only avoiding a double 90ms contribution to the overall delay. As shown in [2], only configurations B2, B3, C. D and R are compliant with the requirement.