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Architectures and Protocols for an Integrated Satellite-Terrestrial Mobile System

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ABSTRACT

This paper aims to depict some basic concepts related to the definition of an integrated system for mobile communications, consisting of a satellite network and a terrestrial cellular network. In particular three aspects are discussed:

- architecture definition for the satellite network;
- assignment strategy of the satellite channels;
- definition of "internetworking procedures" between cellular and satellite network, according to the selected architecture and the satellite channel assignment strategy.

INTRODUCTION

Essentially, there are two ways to implement an integrated satellite-terrestrial mobile system [1]:

1) considering the satellite network as a natural extension and a completion of the terrestrial one, reusing (as far as possible) in the satellite network the same procedures and protocols defined for the cellular one;

2) accepting that the satellite link may be based on specific procedures and techniques, assuming that the integration is obtained only by information interchange at the network side.

In this paper the first viewpoint is considered [2][3] and, to be concrete, architectures and protocols for the satellite network are described with reference to the cellular standard "Global System for Mobile communications (GSM)". An integrated system based on this standard seems possible but problems related to the complete reuse of the GSM protocols on the satellite network have been found. These results could be taken into account to define the future standards for mobile communication systems.

SYSTEM ARCHITECTURE

The reference payload is a geostationary satellite whose feeder link (i.e. the link from/to the "Fixed Earth Stations (FESs)" to/from the satellite) has a global coverage and whose mobile link (i.e. the link from/to the "Mobile Stations (MSs)" to/from the satellite) has a spot-beam coverage.

Basic issues of the satellite system configuration are the number of FESs, the FES-spot connection (i.e. the spots each FES can communicate with), the criteria for the FES-MS association. On these subjects the following issues must be considered:

- a static FES-MS association is proposed. The FES-MS association specifies the FES a certain MS is allowed to communicate with via satellite. Static means that the MS is semipermanently associated to the same FES as long as it roams in a certain spot; conversely, dynamic means that this association can be varied on a real time basis. As it is hereinafter explained, a dynamic FES-MS association permits the "selective landing" and the "alternative routing", but it does not result GSM-compatible.

Selective landing means that, in order to shorten the terrestrial tails, the connection between a MS and a fixed-user takes place through the FES closest to the fixed-user (i.e. the FES is selected on a call-by-call basis on the ground of the fixed-user location).

Alternative routing means that a call routed through a congested FES (or "Base Station System (BSS)") can be rerouted through a different FES (i.e. the FES is selected on a call-by-call basis on the ground of the traffic situation).

In order to permit the selective landing in case of fixed-user originated calls, a stand-by MS should be tuned on the "Broadcast Control CHannel (BCCH)" carrier transmitted by the FES closest to the fixed-user, but, obviously, this is not possible since the MS can not be aware of the fixed-user which is going to call it.

Likewise, in order to permit the alternative routing in case of fixed-user originated calls, a stand-by MS should be tuned on the BCCH carrier transmitted by the "alternative" FES, but, obviously, this is not possible since the MS can not be aware either of the status of congestion of the serving cell or of the identity of the alternative FES.

- Since selective landing is not GSM compatible, in theory, increasing the number of FESs does not yield any benefit in terms of reduction of the average length of the terrestrial tails. In practice, such tails can be remarkably reduced by planning to associate each MS to the FES closest to the area where the fixed-users, which the MS is expected to communicate more frequently with, are located (e.g. the FES closest to the MS headquarter).
- Since alternative routing is not GSM compatible, by increasing the number of FESs per spot, the overall system efficiency decreases due to the partition of the GSM carriers among the FESs. Once the satellite capacity is known, the offered traffic in function of the number of FESs can be easily calculated by applying the Erlang-B formula. In case the above-mentioned efficiency decrease becomes unacceptable, a proper real time reservation mechanism of the carriers should be implemented (e.g. a demand-assignment mechanism with a network control station in charge of carrier assignment). However such a solution entails a remarkable increase in the satellite system complexity.
- As far as the FES-to-spot connection is concerned, the possible solutions range from the simple connection (each FES is allowed to communicate only with a spot, i.e., in general, the spot where the FES is placed), to the full connection (each FES is allowed to communicate with all the spots). Obviously, the full connection solution is more flexible. However, it imposes more stringent requirements on the on-board processor (e.g. a greater number of filters) and/or more complex frequency plans. Moreover, in the full connection solution, each FES must transmit at least a GSM carrier (the BCCH carrier) in every spot and this could be inefficient. The full connection solution can be either "static" or "dynamic". Dynamic means that each FES, in the framework of the GSM carriers assigned to it, can vary, on a real time basis, its carriers-to-spot assignment, in order to cope with contingent traffic situations; static means that each FES can vary the above-mentioned assignment only on a rearrangement basis. Periodic or continuous reconfiguration might be obtained with an on-board switching (controlled via telecomand) of carriers from/to the global beam to/from spot beams. The dynamic solution is more efficient but it requires that the on-board processor and/or the frequency plans are reconfigurable on a real time basis.
- It is more than likely that administrative requirements and/or political matters impose that a certain "Public Land Mobile Network (PLMN)" (and/or a certain country) is provided with its own FES. If this is the case, the MSs registered in a certain PLMN can be conveniently associated to a FES belonging to this PLMN (at least in case this is permitted by the FES-spot connection); so doing, in case of infra-PLMN calls, the passage through external PLMN is avoided.

In conclusion, it is proposed a satellite system configuration in which the number of FESs is kept to a minimum compatible with the above-mentioned administrative/political requirements. In the reasonable hypothesis that the number of GSM channels supported by the satellite system is remarkably higher than the number of FESs, statistical considerations suggest that the efficiency decrease caused by the semipermanent partition of the GSM carriers among the FESs, can be tolerated, thus avoiding the implementation of a complex real time carrier reservation mechanism. The most convenient FES-spot connection can be decided FES by FES depending on the payload characteristics and on the expected traffic between the FES and the spots. As to the static FES-MS association, a suitable criterion is to associate a certain MS to a FES belonging to the PLMN where the MS is registered. In the framework of the FESs belonging to the above PLMN, it is convenient to associate the MS to the FES closest to the MS headquarter. Finally, in case the PLMN where the MS is registered has no FESs (or is not connected with one or more spots), the MS can be profitably associated to the FES (belonging to a different PLMN) closest to the MS headquarter.

CHANNEL ASSIGNMENT STRATEGY

Basically, in an integrated system, the assignment of satellite channels for a communication can be of two types:
1) at the same priority level as terrestrial cellular ones; in that case the choice between satellite and terrestrial resources can be based on link quality parameters (e.g. received signal power);
2) at a lower priority level, recognizing the specific features of the satellite resources (more limited, more costly but able to serve a wide area); in that case the choice between satellite and terrestrial channels should be based on traffic management criteria (e.g. satellite resources are chosen only if the terrestrial ones are not available for whatever reason).

The first approach considers the satellite system as an extension of the GSM network and satellite beams as GSM cells, not only from the architectural viewpoint but also from the operative one: this means that traffic channels, disregarding cellular or satellite, are allocated according to level and quality of the received signal. It has been already shown [4] that this choice leads to a poor network efficiency.

The second choice recognizes that it is unfair to compare satellite and GSM channels on the ground of signal quality and dangerous to allocate a satellite channel when free GSM channels exist in the terrestrial network. This straightforward *selective call set-up procedure* is suggested: *always try to allocate first GSM traffic channels; in case of a blocking state, switch to a satellite channel.*

The proposed strategy discriminates channel types on the base of network criteria (the occupancy state), not simply radio, so that satellite channels represent an overflow for the GSM ones, that remain the primary channels.

Application scenarios

An integrated traffic management strategy overcomes the classical satellite roles of:

- complementing the GSM network in uncovered areas;
- supplying purely additional channels in common areas;

The fixed traffic channel capacity scheme of the GSM system is a severe limitation when the nominal average traffic figures are variable; this may occur on a periodical basis (traffic overloads in specific cells) or because of the customers growth. Cellular networks, are highly vulnerable to such changes while satellite channels, used as overflow resources, can easily absorb the cellular traffic peaks. This feature allows a looser GSM channel dimensioning and avoids periodic reconfigurations.

The customers growth increases the average offered traffic. In this evolutionary process, the satellite can become a powerful planning support for the GSM network, since investments can be postponed. The advantages will be more consistent, if appropriate traffic handling procedures are developed.

An application example

A quantitative comparison between the GSM channel assignment strategy and that proposed in the previous section has been performed on a limited size example where *urban*, *suburban* and *rural* propagation conditions for the GSM network have been reproduced. *Marginal traffic* due to mobile customers roaming outside the GSM coverage but still in the satellite spot beam has been assumed too so that some customers can access only and directly the satellite channels with the same GSM service quality. The "wrong" selection of a satellite channel in the common coverage areas, due to a better received signal, is taken into account in a probabilistic way.

The limited available space suggests to summarize verbally the results. The *System Blocking Probability*, (i.e. the probability that a call is rejected because no traffic channel can be allocated) has been recognized as the most suitable parameter to quantify how the user perceives the quality of service. If overflow to the pool of satellite channels is allowed, local blocking states on GSM cells do not necessarily mean call rejection, as would be for a traffic handling strategy with no overflow. In the simulated example, overflow ensured a reduction of the blocking probability of about 30% with respect to the nominal value.

A second performance figure, the *GSM Network blocking probability*, represents the probability that a call, originating in the GSM network, is rejected. As expected, the nominal blocking probability on GSM cells is reduced by the presence of a supporting satellite system; furthermore, it has been noted that with the overflow capability an increase of the satellite capacity produces, in percentage, a higher decrease of the GSM network blocking probability.

The benefits achieved on both System and GSM Network blocking probabilities are compensated by an increase of the *Satellite Blocking Probability*: this is perceived by mobile customers roaming in marginal areas and those that are better served by a satellite channel in common areas. Such probability is simply expressed by the fraction of calls that access directly the satellite network and are blocked. A partition of the satellite channels that only allows a preassigned amount of channels to host overflow traffic should mitigate this drawback. Dimensioning can be such to optimize the traffic globally handled by the network.

Handover

In cellular networks, handover prevents from forced call disconnections due to signal degradation in the passage between adjacent cells. In the integrated satellite/GSM environment, handover can be extended to the passage from different networks. Two possibilities (GSM-to-satellite and satellite-to-GSM) exist.

GSM-to-satellite handovers can occur when a mobile is leaving the GSM coverage and a satellite traffic channel offers an acceptable quality; hence, they are an extension of GSM handovers. Call continuity is maintained and service quality is increased but they are not traffic management tools.

Satellite-to-GSM handovers, on the contrary, aim at enhancing the overall network efficiency by maximizing satellite channels availability. The function is closely related to the selective call set-up procedure and consists in:

checking the occupancy state of the GSM channels that could be allocated to a satellite conversation; if at least one free channel exists in a suitable GSM cell, the satellite call is handed over to the GSM network.

INTERNETWORKING PROCEDURES

As described in the previous section, traffic interchange between satellite and cellular network may be obtained with the selective call set-up or with the handovers. To define these procedures, it is to be noted that the GSM is already in the development phase and therefore solutions for an integrated system requiring any modification to the existing protocols of the terrestrial network are not reasonable. Modifications, if required, should be confined in the mobile terminal and/or in the ground infrastructure of the satellite subsystem.

Selective call set-up procedure

This definition refers to the MS possibility of establishing a communication through the satellite link when a traffic overload arises in the terrestrial network.

In a cellular network, a set-up procedure to/from a mobile terminal requires some preliminary operations, carried out by the terminal and the network. When an integrated system is considered and a selective call set-up is needed the following aspects have to be pointed out:

- when an MS is not engaged in any type of communication it selects the most suitable cell for communicating over the radio path. In all the considered architectures the spot beams are considered as "macrocells" and the cell search should concern even the satellite band. The frequency band distinction can be exploited to implement the priority selection criterion between terrestrial and satellite network: first the MS searches for a suitable cell in terrestrial PLMNs; in the areas covered only by the satellite system, the selection of terrestrial cells fails due to link quality measurements and the MS switches automatically to the satellite band. If a particular FES-MS association is preferred, it is necessary for the mobile terminal to check first the BCCH of "its own" FES, when it switches to the satellite band: this means that it must keep information about these carriers in its memory.
- The smallest area unit used in GSM for locating the MS is the "location area (LA)": it is composed by one or more "Base Station (BA)"

areas and is identified in a PLMN by a LA identification, which is a parameter broadcasted on the BCCH. A location updating procedure is performed by the MS when it selects a cell with a LA identification different from the one previously received. In an integrated system, we can assign a LA identification to every spot beam, to every FES or to the whole satellite network, according to the adopted architecture. In any case when an MS selects the satellite resources it must perform a location updating.

- When a mobile terminal communicates with the network it has to synchronize its burst transmissions so that they are properly received by the base station in the reserved slots. The synchronization problem of an MS has two aspects:
  - initial synchronization, at the access phase to the network;
  - adaptive correction of the synchronization, during a communication.

The latter aspect may have in the satellite system the same solution as in the GSM. On the contrary, a notably different solution must be used in the first case. In the GSM the *access burst* is received by the BS within the assigned timeslot even if the MS is at the cell boundary. A different situation occurs in the satellite network because of the long propagation delay and the quite large delay variation coming from the position of the MS within the spot beam: due to uncertainty of the receiving instant of an access burst, it is necessary to reserve a carrier to the access in every spot beam. Moreover, to allow FES to evaluate the propagation delay, the MS must send the access burst only at the beginning of specified timeslots.

On the satellite link, as a consequence of the synchronization, the MS performs the transmission of a burst, in a frame, at an instant which does not depend on the instant of reception: then, the timeslot of transmission may overlap to the timeslot of reception. Therefore, unlike a GSM terminal, the MS for the integrated system must have a duplexer.

After these considerations, we can define a procedure for a selective call set-up. We suppose that the MS has selected a GSM cell and that the set-up is not completed owing to a blocking state in this cell. It is suitable to distinguish two cases:
1) *mobile terminating call*: the mobile is the called MS, that is the traffic overload occurs in the "call destination" cell. A procedure for trying an alternative routing through the satellite network is not advisable as, to implement it, modifications should be taken into account in the terrestrial network. As a matter of fact:
- the "Mobile Switching Centre (MSC" that receives the message of *assignment failure* is a GSM MSC and in this system an alternative routing is not provided;
- as previously reported, the MS waits for the *paging* message only on the proper channel of the selected cell. A procedure for a second set-up requires that the MS is registred as located in two LAs, one of which belonging to the satellite network. So, the mobile should perform a location updating for each network and listen to two *paging channels*. This integrated system should work in such a way that the call is first routed through the terrestrial network. A procedure for implementing this set-up type should be more complex than one of the GSM and, in any case, different.
2) *mobile originating call*: the MS has selected a GSM cell and it is the calling terminal, that is the traffic overload arises in the "originating call" cell. When the MS infers that it is not possible to establish the call in the GSM, it tries selecting a beam and, if this attempt is successful, it performs a location updating. Now it can repeat the set-up. The long time required to complete the procedure might be reduced if the MS avoids the first useless attempt. Unfortunately in the GSM, no parameter can be broadcasted on the BCCH to communicate to the MSs the traffic overflow.

GSM-to-satellite handover

Handover from cell to spot beam is a feature not simple to be implemented with GSM contraints.

In the GSM, the mobile, when performing the handover tunes to the "new" BS and transmits an access burst, at the beginning of a slot indicated by the "old" BS. This burst is sufficiently short, so that it is received in the assigned timeslot, even if the MS is at the boundary of the new cell. In a GSM-to-satellite handover, owing to the notable delay involved on the satellite link, it is necesssary for the mobile to have an additional timing indicator, in order that the burst is received by the FES in the assigned timeslot: the MS must know the precise delay, from a defined instant, of the transmission of the access burst. This information should be communicated by the BS and therefore modification to the GSM network would be necessary.

Satellite-to-GSM handover

Satellite-to-GSM handover is one of the most interesting traffic management tool for the integrated system, as it permits to reduce occupancy of the satellite resources.

The criteria that are possible to adopt to start a satellite-to-GSM handover procedure may be different: for example it may be established that this procedure has to be carried out only when the satellite occupancy degree is over a certain fixed value.

To hand over a call from the satellite to the cellular network, it is up to the mobile to allow the satellite network to identify its position inside the beam: this may be achieved with the message *measurement report*, sent periodically by the MS. In it the identity of at least one cell, among those reported by the mobile, must be indicated with its complete identifier, that is broadcasted on the BCCH and allows to distinguish the cell inside the whole network. Obviously, it is suitable that cell specified by the MS is the one from which the received signal strength is the highest, since, presumably, the mobile is there.

Recall that, in the GSM, the neighboring cell BCCH frequencies to be monitored are communicated to the mobile through a well defined list, transmitted by the serving cell. Analogously, when the mobile communicates through the satellite, in this list the FES should indicate the frequencies that are BCCH carriers in the area where the MS is at this time. In other words, the FES should adapt the transmitted list according to the position of the mobile in the beam. This requires the mobile knows the GSM cell where it is immediately before the set-up. This condition excludes a handover from satellite to GSM, when the set-up occurs outside the GSM coverage. Instead the mobile may precise the cell when it accesses the satellite owing to the traffic overload in the terrestrial network.

Other problems may be due to the MSCs of the terrestrial network. Note that a "terrestrial" MSC overlaps to the neighboring MSC areas only with the boundary cells of its coverage area. So an inter-MSC handover should occurs only between boundary cells of two MSCs. This fact might be taken into account in the implementation of the terrestrial network. Instead, in order to hand over the calls from the satellite to the GSM, all the cells inside a terrestrial MSC area should be considered boundary cells with respect to the area covered by the satellite MSC. The exploitation of this feature depends on the national implementation of the GSM.

CONCLUSIONS

An integrated system based on the GSM procedures allows to increase the efficiency of the cellular network and seems actually feasible. Some drawbacks related to the reuse of the GSM protocols have been highlighted. The design of a fully integrated system, for the next generation of a Personal Communication System, should take into account these drawbacks and define the architecture and protocols in such a way that the satellite network more naturally fits into the overall network.

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