THE SYNERGY OF SPATIAL AND TERRESTRIAL COMMUNICATIONS IN NEXT-GENERATION HYBRID WIRELESS SYSTEMS

INTEGRATION OF SATELLITE AND TERRESTRIAL SYSTEMS IN FUTURE MULTIMEDIA COMMUNICATIONS

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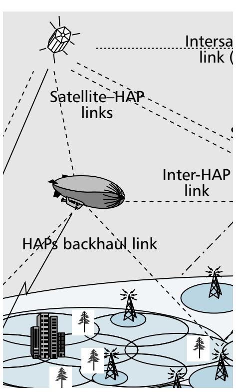

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ABSTRACT

In this article we examine the role of satellite communications in future telecommunication networks and service provision. Lessons from the past indicate that satellites are successful as a result of their wide area coverage or speed to market for new services. Niche areas such as coverage of air and sea will persist, but for land masses convergence of fixed, mobile, and broadcasting will dictate that the only way forward for satellites is in an integrated format with terrestrial systems. We outline future ways forward for satellites, and discuss the research challenges and technology advances needed to facilitate this integrated approach.

INTRODUCTION: WHAT ROLE FOR SATELLITES?

The evolution of telecommunication systems is influenced by three interconnecting factors (Fig. 1): advances in technology, development of new services, and traffic growth. Technology advances such as high-speed processors and small size high-capacity storage discs bring exciting new multimedia services such as entertainment and games, and enable their delivery to cheap terminals at affordable prices to the consumer. Customer demands thus increase and, with them, traffic growth in networks. In order to cope with this avalanche effect, communication systems must evolve either within themselves or via the creation of completely new networks suited to the new service provisions. This article concerns this evolution and the provision of a range of new multimedia services in an efficient, secure, and cost-effective environment. The premise is that this can only be accomplished by integration of networks, specifically integration of terrestrial and satellite networks

Satellite broadcasting and mobile satellite systems to cover air and sea are established markets, but elsewhere satellites have not been shown to compete well with terrestrial service provision. However, we should recall the unique features of satellites: wide area coverage and speed to deliver new services to the market. These will be key to the delivery of affordable future services and the choice of satellite as the preferred delivery mechanism.

Due to the dominance of Internet-based multimedia applications and changing customer trends, and hence changing market and business models [1], satellites cannot afford to focus on a specific type of service as in the past. From a technical point of view, delivery can be split into two service types: fixed and mobile. The two types of delivery mechanism, unicast and broadcast/multicast, are applicable to both service categories depending on the number of pieces of user equipment receiving the same multimedia content from the same source at the same time.

From the wide area perspective, the satellite can still maintain exclusive status in the traditional maritime and aeronautical markets due to its unique coverage feature. Wide area coverage has in the past meant lower powers and hence poor efficiency. As the demand grows from passenger vehicles for broader-band multimedia services, satellites need to become more efficient in their delivery, exploiting new technologies such as multibeam antennas and onboard processing.

In the coverage of land masses satellites do not have such exclusivity. Both fixed and mobile

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coverage on land masses via cable and second-generation mobile (e.g., Global System for Mobile Communications, GSM) are well advanced; it is only in the more remote rural areas that satellite is needed, and these markets are small, although politically important. Eighty percent of the world's population lives in urban/suburban areas, covering 20 percent of the world surface area. Therefore, satellite can only target 20 percent of the population if the satellite industry relies on rural and remote areas This may be even less if we consider Europe, in which GSM has reached 88 percent of the territory and addresses 97 percent of the total population in France, which has the largest land mass and is the most sparsely populated country in Europe.

The rollout of the new third-generation (3G) mobile networks (e.g., Universal Mobile Telecommunications System [UMTS] in Europe) is in its infancy. Here speed could be an edge for satellites in the early stages, but this competitive approach is not ultimately sustainable. Thus, the idea of *complementary coverage* between terrestrial in urban/suburban areas and satellite in rural areas is logical, and such integrated provision would seem to be attractive.

However, there is possibly a more appropriate opportunity for satellites in the mobile arena arising from recent increased demand for multicast and broadcast services on the move. Here again we return to the basic advantages of satellites: wide area coverage and speed of new services to market. Considering the inherent difficulty of efficient provision of multicast/broadcast services with smaller 3G cellular systems, we conclude that this is a perfect role for satellites, which can now serve tens of millions of users and thus move from their traditional niche to the mass market. However, users do not want multiple terminals, so real efficiency only results from integrating this service with other 3G services being provided terrestrially. This is the *cooperative service* delivery approach in which we integrate the two service types into a single terminal. In order to provide coverage in urban areas, it is necessary to relay the satellite transmissions via some of the base stations, but in the adjacent mobile satellite service (MSS) bands. Of course, it is possible to deliver multicast/broadcast by other means, e.g., terrestrial digital audio broadcasting (DAB) and digital video broadcasting-mobile (DVB-H) standards, but integration is still key, and economics will dictate which system eventually wins out. These are all examples of the convergence of mobile and broadcasting.

Turning now to fixed rather than mobile systems, we note that the heritage of satellite has been the point-to-point (unicast) transoceanic high-capacity connections between major operators. As technology has advanced via digital optical submarine cables, this once exclusive satellite market has diminished to one of largely backup or diversification. The dot.com boom of the mid-1990s and the dependence on the Internet for day-to-day activities has increased traffic demands from Internet service providers (ISPs). Satellites have responded to this rapid demand by providing high-capacity digital IP circuits at a speed that could not be matched terrestrially in the developed world, and may never be in the developing world. Operators in this arena have already embraced the integrated approach by using the IP protocols with only minor fixes to get them to work over satellite. Thus, they offer the full range of services almost seamlessly between terrestrial and satellite in the core network.

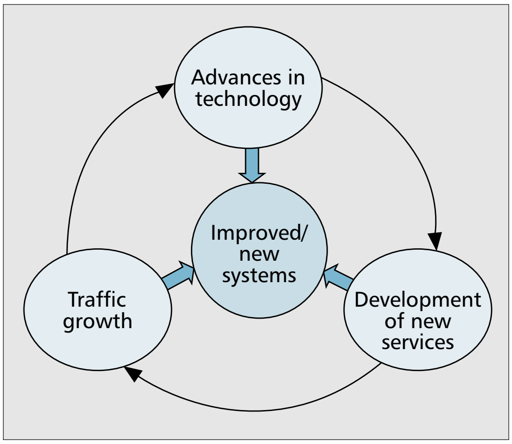
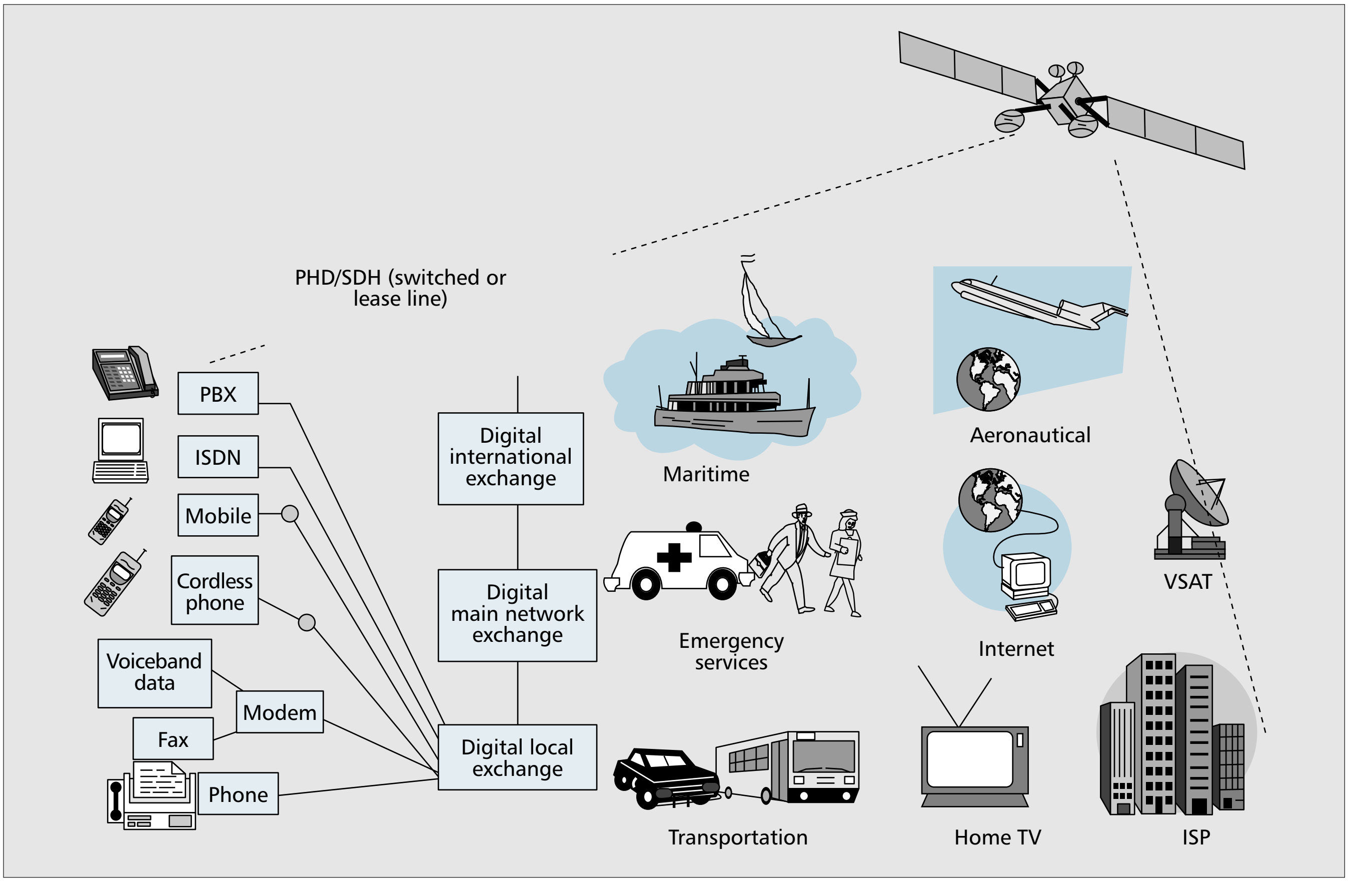


Figure 1. *Telecommunications system evolution.*

It is possible to deliver the multicast/broadcast by other means, such as terrestrial digital audio broadcasting and digital video broadcasting-mobile standards, but integration is still the key, and economics will dictate which system eventually wins out.

While satellites have found their place within the core network, what about the access network? Here we have a similar scenario to that in the mobile network. The initial rollout of broadband fixed access (digital subscriber line [xDSL] cable or broadband wireless access [BWA]) was slow, and satellite was able to fill the speed to market niche in some areas. However, just as with GSM, in most developed countries terrestrial rollout has now caught up with demand, and satellite is relegated to countries with difficult geographies and extremely rural areas. In these, the markets and revenue potential are smaller. The ability for satellite to compete head on with terrestrial in developed countries relies on major efficiency improvements in future satellites, discussed further later in this article. This would again point us to integration as the way forward and imply that common standards that allow interchangeable provision between the two domains must be developed. This, however, requires operators and equipment manufacturers to think in terms of cooperation rather than competition.

Returning to the advantages of satellites, and wide coverage broadcast services. Satellite TV broadcasting has, perhaps obviously, been a lasting and major success. Direct-to-home digital broadcasting via satellite accounts for 80 percent of the provision of service in Europe where DVB standards S and S2 have been extremely successful in the delivery of affordable mass market terminal equipment. This is the one area in which satellite has been in the vanguard over cable and radio. It is interesting to note that although limited interactivity is provided, the feedback channels are normally terrestrial (some integration here). The extension of the DVB standards to a return channel via satellite (RCS) has not yet been as successful because it is still inefficient and uneconomic for the mass market. However, such systems do have the potential to provide integrated broadband access and TV services in the future. Several U.S. [2] as well as European industry analysts [3] have also spotted



■ **Figure 2.** *Satellite services and coverage.*

the advantages of such synergy with DBS companies that have already developed relationships with customers.

Thus, we conclude that satellite systems should have the flexibility to support a range of multimedia services (Fig. 2) and that for these to be delivered economically, there is need for integration with terrestrial systems — satellite systems cannot exist in isolation except in niche areas.

In order to determine what is needed to bring about this integration, we first look at the well developed vision for terrestrial niche networks and then at the historical evolution of satellite systems themselves. Using these, we propose a future integrated network architecture scenario and finally address the technology advances needed to realize it.

Technology Trends and Terrestrial Network Visions

Nowadays people depend more and more on advanced communication technologies such as the Internet, computers, and mobile phones, and would like to have these technologies anywhere and at any time. The requirements born from this specific demand can be listed as follows:
- Access to all types of telecommunication services
- A single device to communicate with different networks
- A single number (or IP address)
- A single bill for all services with reduced cost
- Reliable wireless access even in the failure of one or more networks

These requirements push today's vertical network approach with single services toward a horizontal network approach with multiservices, as shown in Fig. 3.

In order to implement this horizontal approach, the telecommunication industry is searching for a generic radio access network connected to a unified IP-based core network. The difficulty is that there are already several access technologies available, and these have been developed independently for special purposes. Therefore, interworking between different access systems is becoming a key issue for future systems.

Even though the different access systems have been developed separately, they do complement each other under a layered concept, as shown in Fig. 4, in terms of coverage and capacity. The broadcast layer will have the capability to cover large areas and handle full mobility; however, capacity is lower than with other layers. The technologies used in this layer can vary from DVB/DAB to 3G Partnership Project (3GPP) UMTS to a system such as S-DMB (satellite digital multimedia broadcasting) currently under study. The cellular layer includes 2G and 3G systems and supports up to 2 Mb/s depending on mobility conditions. This layer supports full mobility using handover techniques. The hot spot layer supports very high data rates, but mobility is restricted. Personal area networks are meant for offices and homes to communicate with dif-

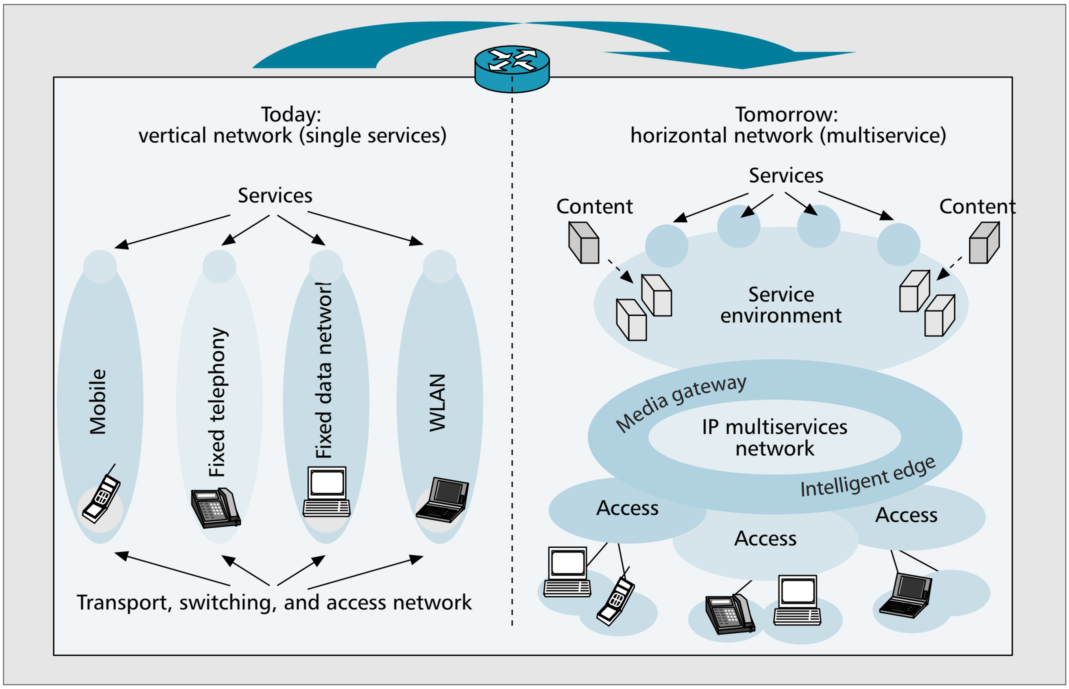


Figure 3. *Moving from single services to IP-based multiservices.*

There needs to be efficient coverage of the hot spots as well as wider area mobility coverage provided by the satellites. In providing the focused interworking, the challenge is not to block the ultimate goal of integration.

ferent appliances (refrigerators, toasters, washing machines, smart sensors, etc.) and have capacities of hundreds of megabits per second. The fixed layer contains optical fiber (e.g., fiber to the home/curb [FTTx]), twisted pair systems (e.g., xDSL), and coaxial systems (e.g., CATV) as well as fixed wireless access systems (e.g., WiMax). This is the Wireless World Research Forum (WWRF) vision of a future wireless world [4].

Based on the above mentioned customer requirements and technology trends, the expected peak data rate for systems beyond IMT-2000 is defined as 100 Mb/s for new mobile access and 1 Gb/s for new nomadic/local wireless access. This data rate can only be achieved widely if the frequency resources are used efficiently. Therefore, research activities in terrestrial systems are mainly focused on the radio network issues listed below.

More efficient air interface structures [4]:
- Orthogonal frequency-division multiplexing (OFDM)-based multicarrier code-division multiple access (CDMA)
- Multiple-input multiple-output (MIMO) systems, smart antennas, and space-time coding
- Adaptive modulation and coding, power control, equalization, and diversity

More efficient networking:
- Dynamic channel allocation; admission, load, and congestion control
- Adaptive handover strategies
- Ad hoc networking
- Cross-layer (IP) mechanisms

More efficient use of the radio spectrum:
- Dynamic spectrum allocation
- Software and cognitive radios

Most of the above can also be employed to improve efficiency of the satellite system, but there are challenges in doing so while retaining flexibility with compatible standards to allow integration between satellite and terrestrial systems.

From Fig. 4 we note that there must be interworking (vertical connections) between the satellites at the top and the cellular, WLAN, PAN, and fixed systems lower down. There needs to be efficient coverage of hot spots as well as wider-area mobility coverage provided by the satellites. In providing focused interworking, the challenge is not to block the ultimate goal of integration.

We now go on to review the evolution of satellite systems to determine the constraints this imposes before returning to these challenges in more detail.

Satellite Communication Historical Evolution

Mobile Satellite Systems

We show in Fig. 5 some of the key landmarks and major mobile satellite systems (MSSs) that have resulted from them. It is interesting to note that INMARSAT came into existence at around the same time as the first cellular operators providing first-generation analog services. In its initial period, INMARSAT provided speech and low-data-rate services mainly to the maritime market of larger ships in the L band using global beam coverage satellites. In 1990–1991, INMARSAT added aeronautical services to passenger aircraft and some land vehicles with the introduction of higher-power spotbeam satellites. This was followed in 1997–1998 with worldwide spotbeam operation in MSSs and the introduction of paging, navigation, and higher-rate digital to desktop-sized terminals. INMARSAT has concentrated on the use of geostationary (GEO) satellites, and in the mid-1990s several regional GEO systems emerged in competition (e.g., OMNITRACS, EUTELTRACS, AMSC, and OPTUS), concentrating on land vehicles and using both L and Ku bands. These were only moderately successful, while INMARSAT

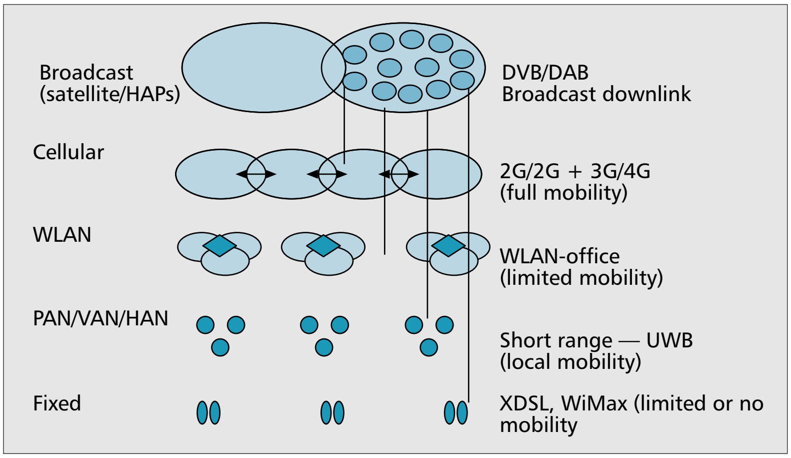


Figure 4. *Layered networks.*

has built its customer base to around 250,000. The major research in the late '80s and early '90s was directed to non-GEO constellations, principally to facilitate the link budgets and reduced delay for voice services to handheld terminals, and this saw proposals for low Earth orbit (LEO) and medium Earth orbit (MEO) satellite systems based on constellations of 10–66 satellites for global coverage. Of these, Iridium and Globalstar came into service, but too late to compete with the spread of terrestrial GSM, and on business rather than technological grounds went into Chapter 11 bankruptcy by the early 2000s. The lesson learned was that constellations were too expensive, at up to $10 billion to deploy, unless markets had large initial growth to provide rapid payback. Both systems are in existence today but with fewer customers than initially predicted. (Orbcomm, a little LEO provider mainly to fixed terminals, suffered a similar fate). ICO, the proposed MEO system, got as far as launching one satellite before also realizing that the business case was not there.

To help the future development of the mobile satellite industry, a European Task Force on Advanced Satellite Mobile Systems (ASMS-TF) was formed in 2001, and operates today in the fields of research and development, standards, and regulatory matters [5].

In the mid-1990s, larger so-called super GEO satellites were proposed, with powers around 5 kW and with 100–200 spots rather than the earlier generation of GEOs with 3–4 kW and 5–10 spots. Several such systems were proposed, but the one that successfully entered the market in the early 2000s is THURAYA, based on the European Telecommunications Standards Institute (ETSI) GMR-1 standard, providing GSM and General Packet Radio Service (GPRS)-like services covering Asia and parts of Europe. Although it is early days, these super GEO systems seem to be successful, finding a niche with travelers, trucks, and in areas where terrestrial mobile is expensive to deploy. Meanwhile, INMARSAT is providing its own super GEO, INMARSAT IV (first launched in the first quarter of 2005) to take existing digital services from 64 up to 432 kb/; from the global area network (GAN) to the broadband GAN (BGAN). Despite the move by terrestrial mobile operators to CDMA, INMARSAT has continued to develop its proprietary time-division multiple access (TDMA) system but delivers 3G-equivalent packet-based services.

So the lessons learned from the mobile satellite experience are:

- LEO and highly elliptical orbit (HEO) constellations have proved too expensive to compete with GEOs or cellular systems, so there is now a return to GEOs.
- Satellites can only economically provide niche services to areas inaccessible to cellular; hence, for mass market services there needs to be integration, not to compete but to collaborate with cellular.
- Select the service most appropriate to the satellite delivery mechanism.
- Use the wide coverage broadcast attribute of satellites.

Based on the above factors, the satellite digital multimedia broadcasting (S-DMB) system was proposed within European Union (EU) projects SATIN [3], MoDiS [6], and MAESTRO [7] to deliver multimedia broadcast and multicast services (MBMS) to users in terrestrial cellular coverage as well as outside. The proposed S-DMB system is mainly centered around content delivery or push type services where the content is pushed toward the terminals whenever the resources are available and stored in the terminal local cache memory for later retrieval. The architecture is characterized by gap-fillers or intermediate module repeaters (IMRs) located at selected 3G base stations, which broadcast the MBMS signals terrestrially in the adjacent MSS band to allow in-building and urban area penetration.

A similar concept has been adopted within the MBSAT [8] system now in operation in Japan and Korea, where the service driver is mobile television rather than video content. Such systems have competition from MBMS in 3G and from DVB-H, but offer a real new market opportunity for satellite and, most important, the first truly integrated system delivery.

The DAB systems via satellite S-DAB (DARS in the United States) should also be mentioned in this context as radio broadcast is a further example of content delivery. The idea has been around since 1990 when CD radio first filed in the United States. Several systems have been proposed since the S-DAB standards were produced with WORLDSPACE [9] in the mid-1990s being perhaps the leading contender with its satellites covering Asia, the Caribbean, and the Americas.

The terrestrial equivalent, T-DAB, has not spread widely, with the limited U.K. network being perhaps the best developed. In the United States, in the early 2000s two commercial systems became operational: XM Radio using GEO satellites, and SIRIUS satellite radio using HEOs. Both systems use terrestrial gap fillers in a similar way to that proposed by SDMB and MBSAT. The use of HEO satellites is interesting in that they achieve improved coverage in the urban area due to their higher elevation angles and reduce the number of gap-fillers required. Currently XM has around 3.5 million and SIRIUS 1.5 million customers in the US.

When we consider mobile broadband by satellite, the major market is for passenger vehicles (aircraft [10], ships and trains/coaches) except the INMARSAT BGAN system, where a wider range of customers are perhaps more likely to use broadband services. Connexions by Boeing (CBB) [11] began operating broadband links to aircraft in 2002 and is now pursuing the maritime operators market. The technology here has been more akin to the very small aperture terminal (VSAT) model with local in-vehicle distribution. CBB has already installed terminals with a number of airlines. VSAT systems started in the offshore oil business but have rapidly expanded to cruise liners and deep sea ferry operators using Ku band, and provide commercial, engineering, and navigation services to passengers and crew. A number of satellite operators carry such services. Extensions can also be made to land vehicles, and EU Framework Programme 6 (FP6) projects DRIVE/OVERDRIVE [12] and FIFTH [13] have researched the train/coach/car markets.

The above broadband schemes still suffer from poor efficiency of use of satellite capacity, which makes them expensive. A solution to this may be around the corner with the introduction of the new DVB-S2 standard in 2003 [14]. Principally aimed at fixed systems, it incorporates adaptive coding and modulation (ACM) schemes that, when operated in connection with the return satellite channel (RCS), allow transmission parameters to be optimized for each individual connection dependent on path conditions. A range of phase shift keying (PSK) and adaptive PSK (APSK) modulation schemes and LDPC codes provide packet-by-packet optimization to meet adverse changing channel conditions. The new standard allows a range of data inputs including IP. Combining the DVB-S2 ACM scheme with multispot Ka band satellites and a DVB-RCS return link, current satellite capacity can be increased by a factor of 10 or more. The next step is to introduce mobility into the standard, which will then enable it to be used for broadband mobile multimedia connections as mentioned above.

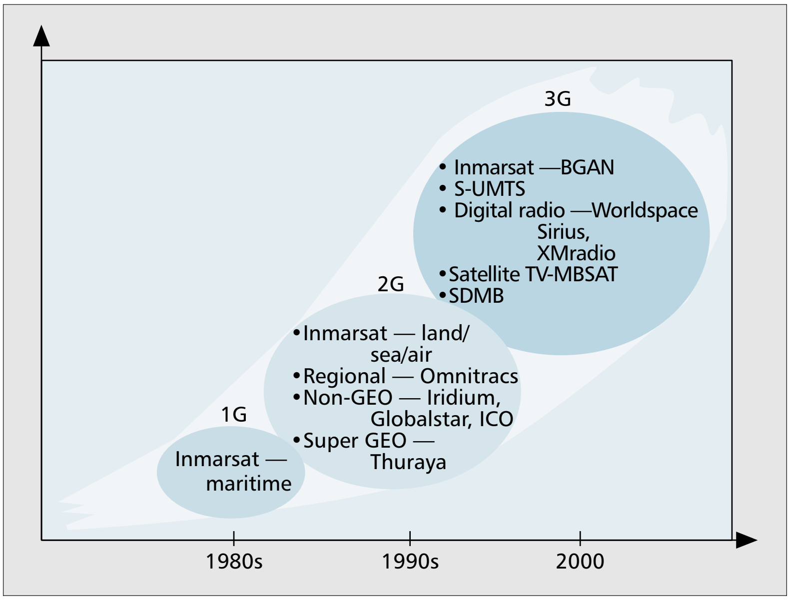


Figure 5. *Mobile satellite development.*

Fixed Satellite Systems

Fixed satellite systems continue to play an important role in the core network where, on a point-to-point basis, they can still compete with terrestrial links in some areas in which their coverage and reduced ground infrastructure are advantages. Major international satellite operators such as INTELSAT, SES GLOBAL, and EUTELSAT remain viable businesses. It is interesting to note that their business models have evolved; they have moved from IGO status to private companies. They have moved from selling bandwidth to selling service connections — from megahertz to megabits per second — and now have ground infrastructure as well as satellites among their assets. The industry has evolved very conservatively, and the vast majority of satellites are still of the transparent transponder type operating in C, Ku, and Ka bands, but with increasingly complex multibeams. The digital pipe remains the major success using frequency-division multiple access (FDMA), with TDMA and satellite switched TDMA (SS-TDMA) introduced but not really catching on. Satellites have remained of the transparent type with the exception of some digital TV broadcast satellites that have embraced limited onboard switching. Full onboard processing has been considered too risky due to lack of flexibility of the channel allocations and bit rates. On the other hand, traffic has changed, with IP now a major percentage of the whole via ISPs. Satellites have remained low to medium power, which has meant low efficiencies of usage of the radio spectrum compared to terrestrial systems. As with mobile, we have seen fixed satellites develop separately from terrestrial in both standards and operators with little if any integration of provision.

The success of DVB-S/S2 standards in Europe has also led to two-way systems incorporating VSATs at either Ku or Ka band return, the RCS system. These have been found to be alternative ways of delivering IP services and incorporating mesh networks. However, the efficiency of IP delivery still falls short of terrestrial where asymmetric DSL (ADSL) still rules supreme in developed countries.

VSAT networks in Europe have not really taken off as expected and have not achieved the size or volume of U.S. counterparts; cost and efficiency are the main reasons.

The final area of usage of fixed satellites has been in broadband access where coverage and speed of implementation have been the niches. Rural and suburban areas across Europe and particularly in Eastern Europe have been regions where satellite terminals have been extensively deployed so far. However, as ADSL is rolled out progressively in the more developed countries, the greater cost of the satellite cannot compete. There is much talk of the digital divide (or is it a poverty gap?), and no doubt that vast areas of Europe will not be covered by cheaper terrestrial means. However, it will take political will to solve this problem using satellites, as it is difficult to see how pure economics will support satellite delivery.

So the messages for future fixed satellite systems are:

Based on business and market observation in the recent past, the satellite community must definitely look at the satellite as an integrated part of the global telecommunication infrastructure rather than as an individual entity.

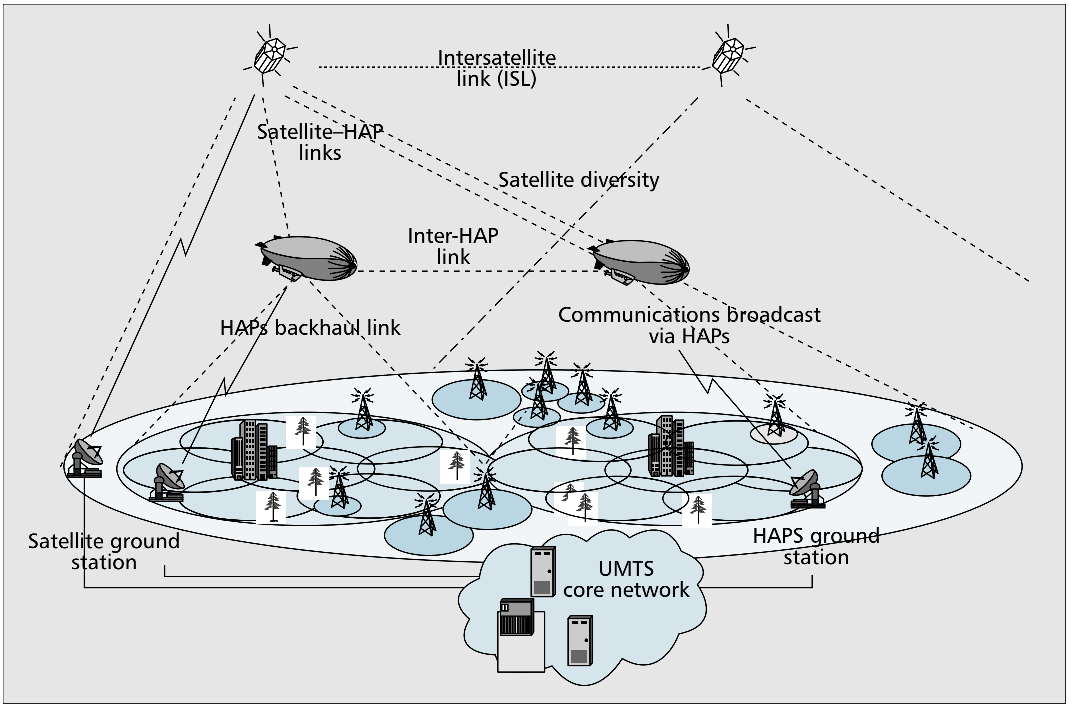


Figure 6. *Possible integrated system architecture.*

- Greater integration with terrestrial systems, as satellites cannot compete in urban/suburban areas but are more efficient in rural areas. Adopting compatible standards will allow cheaper equipment and flexible offering by operators.
- Increase of system efficiency. In order to reduce the cost per bit with satellites of limited power, they must adopt advanced technologies in advance of terrestrial systems to achieve needed efficiency gains of 50–100.
- Onboard processing that is flexible with large numbers of interconnectable beams is needed, and this means moving up in frequency bands to Ka and above. Onboard processing must allow variable bandwidth channels to enable flexibility of service usage.
- Scalable systems of smaller and more powerful satellites in order to avoid the very high up front system costs. Such satellites can be interconnected in orbit, and expand and reconfigure as demand grows.

System Architecture and Technology Issues

Based on business and market observation in the recent past, the satellite community must definitely look at the satellite as an integrated part of the global telecommunications infrastructure rather than as an individual entity. This phenomenon is going to be the basis for future satellite system architectures; a possible generic system concept is depicted in Fig. 6.

This depicts an all-IP network with end-to-end connections and guaranteed quality of service (QoS). There is complete integration between terrestrial fixed, cellular, and hot spot connections with dynamic ad hoc routing between networks. The interconnected satellite layer provides the wide-coverage larger cells and mobility management between the various networks. A subsidiary layer of intermediate-sized cells is provided by high altitude platforms (HAPs) located at around 20–25 km in the stratosphere to deal more efficiently with hot spot areas and relieve the demands on terrestrial infrastructure as well as collection for lower-power sensor networks and broadcasting to urban areas. All networks are vertically and horizontally connected, as indicated in Fig 4, and seamless and secure handover between them is provided. This is a vision, and in the following we look at the components that will be needed to realize the vision.

Satellite Constellations and Payloads

In the immediate future, the choice may be between GEO and HEO since in urban areas the probability of direct reception from a HEO satellite is higher than from GEO satellites; hence, there is reduced blockage, and fewer terrestrial repeaters are required [15]. However, LEO/MEO will come onto the scene in the longer term due to availability of sophisticated small (hundreds of kilograms) satellites with cheaper prices for production and launching. Clusters and swarms of such satellites, maybe with fragmented functions and connected together via an in-space ad hoc network, will be possible.

HAPs, although not strictly satellite, can also play a role in both mobile and fixed satellite service delivery. For the emerging sensor network/ security systems, they could be more efficient standalone than satellite for lower-power terminals or sensors. They could also play a role in a hybrid network of satellites and HAPs where there is much to be gained from use of hybrid orbits with interorbit links in terms of connectivity, coverage, and service routing.

When we consider future payloads there are two main choices, bent pipe (transparent) and

onboard processing (regenerative), with the following key technologies:
- Larger deployable reflectors up to tens of meters in diameter to increase power efficiency
- Higher-power multibeam antennas with adaptive beam shaping via digital signal processing (DSP) to improve power in directed areas dynamically
- Scalable digital processing, enabling improved connectivity
- Lighter and reduced volume components with onboard wireless connections to reduce launch costs
- Short-range ad hoc satellite clusters to achieve scalable growth

Transparent payloads are considered to be more flexible and conservative than onboard processing. However, regenerative payloads offer a number of benefits, such as efficient spectrum sharing, reduced delay, improved link budgets, and possible seamless integration with terrestrial networks. But so far they have not been sufficiently flexible, as it is difficult to design payloads taking into account different transmission formats. However, research on software radio can be applied to this problem to solve the flexibility issue in the future [16].

Radio Interface and Networking Issues

Much greater emphasis has to be put onto the efficiency of the physical layer by use of fade mitigation techniques (FMT) [17], particularly ACM schemes [18], which are easier to implement in the fixed than in the mobile environment. The use of FMT at the higher frequency bands will be implemented and become a part of the radio resource management (RRM)/ medium access control (MAC — part of layer 2) schemes [19]. More efficient MAC will incorporate RRM in a packet-based environment with adaptation of user traffic. Distributed RRM, in the same way as in mobile systems, is a key research area, and mobility management is no longer limited to a single-layer approach. There will be a need to look at cross-layer protocol schemes, where signaling information will be exchanged even between nonadjacent open systems interconnection (OSI) layers, in order to improve the efficiency of delivery within the IP network. RRM optimization with cross-layer information can address several aspects:
- In the physical layer, radio channel conditions will be estimated to select one from a set of possible transmission modes with related resource requests at layer 2 to improve RRM and MM.
- In the link layer, network-specific MAC techniques can be utilized by the IP layer to improve handover performance.
- In the network layer, a packet-switched system employing IP should be adopted by the satellite system in order to be integrated with terrestrial next-generation networks. IP-layer QoS and mobility provision (i.e., integrated or differentiated services) should be adequately mapped to RRM protocols.
- In the transport layer, an interesting example is to perform dynamic bandwidth allocation where resources are requested in advance depending on the expected behavior of the TCP congestion window. Multihoming and reliable transport layer mobility can be supported with dynamic IP address reconfiguration. Another possibility is offered by joint transport/physical layer forward error correction coding design for improved QoS without retransmissions.
- In the application layer, different (real-time or non-real-time) traffic types should have distinct QoS characterization, thus entailing different priorities to be adopted at layer 2. Also, application layer mobility mechanisms such as Session Initiation Protocol (SIP) can interact with IP mobility management to improve handover.

Besides the above considerations, issues related to mobile satellite air interface compliance with the terrestrial mobile air interface and the thrust by the terrestrial mobile community toward OFDM-based air interfaces have also spurred interest in OFDM-based satellite air interfaces. Therefore, special satellite features (e.g., payload nonlinearity distortion) that affect OFDM performance have to be investigated thoroughly. The research so far has shown that the OFDM scheme with efficient predistortion techniques and powerful codes can provide much better performance over satellite links than wideband CDMA (W-CDMA) [18].

We are likely to see some moves toward integration as satellite and terrestrial operators merge and start to consider more integrated provision. In this respect, interworking issues and standards are likely to be very important.

Spectrum

Currently existing mobile satellite systems (INMARSAT, THURAYA, MBSAT, etc.) operate in the L and S bands. In general, the lower microwave bands are easier and more efficient for mobile applications as no tracking is required and terminal equipment can be made cheaper. In addition, if integration is to be pursued, satellite bands should ideally be adjacent to those allocated for terrestrial mobile to again ensure affordable terminals. Thus, the demands will be for more spectrum in the 3–6 GHz regions for both services. The Ku band, primarily allocated for fixed services, is being used on a noninterference basis for some mobile applications (e.g., CBB). For passenger vehicles the greater expense of the tracking antenna required can be acceptable but is problematic for personal use. Allocations at the Ka band and above for mobile, apart from the passenger vehicle niche, are further limited by equipment costs.

For fixed satellite systems the Ku band is the current workhorse for all operators (INTELSAT, EUTELSAT, PANAMSAT, SES-GLOBAL, etc.) with Ka band gradually being introduced for unicast services. In some cases combinations of the bands are used, for example, in smaller customer terminal equipment with higher-capacity outbound links at the Ku band and lower capacity at the Ka band on return. This is dictated by interference issues as well as equipment costs. As multimedia service demands increase, there will be a move to Q/V bands at 40/50 GHz, but here equipment is still expensive and FMT will almost certainly be required to combat the increased propagation losses. However, there are upsides in moving to the smaller wavelengths where smaller physical sizes of antennas benefit the spacecraft real estate

Regenerative payloads offer a number of benefits, such as efficient spectrum sharing, reduced delay, improved link budgets, and possible seamless integration with terrestrial networks. But so far they have not been sufficiently flexible.

Looking further ahead, research into the use of optical frequencies for earth-to-space paths is already underway, but perhaps these frequencies will be better employed outside of earth's atmosphere for inter satellite and satellite-HAPS connections.

restrictions and enable the production of a larger number of smaller spot beams. The latter is key to improving satellite payload efficiencies. An additional advantage is that these bands are much closer to those allocated for HAPs and hence would aid the integration of the two systems.

Looking further ahead, research into the use of optical frequencies for earth-to-space paths is already underway, but perhaps these frequencies will be better employed outside of Earth's atmosphere for intersatellite and satellite-HAPs connections.

CONCLUSIONS

In this article we have examined the impact of satellites in the future global communication system. Satellite systems would need to make major leaps in efficiency in order to compete with terrestrial networks in developed environments, and it is not clear they can do so. We have hopefully demonstrated that the future of satellite is very much in an integrated architecture with terrestrial systems to provide multimedia services, be they mobile or fixed systems. Of course there will still be a role for satellites in niche areas in air or at sea, and to address new areas of disaster relief and security (e.g., sensor networks). Although we see a future for hybrid orbits and even HAPs, this can only be in a fully integrated system architecture together with terrestrial; the future is definitely integrated.

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