R&D DIRECTIONS FOR NEXT GENERATION BROADBAND MULTIMEDIA SYSTEMS: AN ESA PERSPECTIVE

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ABSTRACT
The scope of the present paper is to outline ESA’s R&D directions for the development of new technologies required for future broadband satellite communication systems. The document outlines likely trends and technological issues that will need to be tackled in the medium and long term (e.g. 5 to 10 years) to improve by more than one order of magnitude satellite communication networks efficiency, thus increasing their economical appeal. It is shown that by timely developing in a co-ordinated fashion a number of techniques and technologies encompassing both ground and space segment it is possible to attain the ambitious target set forth above.

INTRODUCTION
Despite the continuous progress witnessed in terrestrial fixed and wireless communication networks capabilities, satellites are still an attractive solution for broadcasting, multi-casting and point-to-point communications for their well known coverage capability, limited ground infrastructure requirements and flexibility. However, current on-board and on-ground satellite technologies are losing their competitive edge in front of the aggressive deployment of new terrestrial access (UMTS, ADSL, DAB, DVB, LMDS etc…) and transport technologies (DWDM, SDH, ATM…). Satellite networks technologies are today often lagging behind terrestrial ones and they are not flexible enough to efficiently support the current trend toward bursty non-uniformly distributed traffic, both in space and time. However, this is not an intrinsic limitation and satellites, provided that the necessary technology is developed with proper timing, can actually offer advantages in that respect since they inherently serve larger areas.

Another issue of concern is the fact that efficient regenerative transponders, although technically feasible, are still considered risky because of their limited capability to adapt to terrestrial network evolutions during the satellite lifetime of ten or more years.

Although multi-media satellite systems currently being developed are representing a significant milestone in making satellite recognized as an important component of global telecommunication infrastructure, there is still a considerable room for improving their effectiveness and flexibility to accommodate future networks requirements.

To be successful the next generation of satellite communication networks shall be able to satisfy telecommunication, broadcasting and dissemination needs for next decade by improving the integration with terrestrial network and increasing the overall system efficiency also by lowering space segment deployment and exploitation cost by a factor greater than 10. To achieve the above targets, so as to be able to respond to future communications requirements by means of space-based solutions, it is required to develop truly innovative systems keeping in mind current limited attitude to risk and the difficulty to anticipate market trend. This will require the development of a new generation of satellite systems, payload architectures, ground technologies and techniques combining flexibility with cost effectiveness. The focus here is not on assessing market opportunities for broadband systems but rather on identifying forthcoming techniques and technologies that are likely to provide a definite chance that space and ground segment would drastically benefit (in terms of electrical performance and cost effectiveness), in the future, from such evolution.

SYSTEM ASPECTS
Looking to the future is very difficult to forecast what satellite networks and applications will look like. Here we just attempt to make an educated guess on which directions current architectures are going to evolve.

Application Scenarios
For what concerns broadband data networks the main player today is Internet who represents the largest public packet switched data network based on the end-to-end principle (distance independent) and typically providing best effort services. The key players are represented by infrastructure providers of physical and permanent virtual circuits, service providers building packet
switched networks and providing internetworking agreements between service providers and users. The current user applications are mainly narrow-band and follow client-server model (e.g. web, e-mail, ftp). Future main network features can be summarized as different Quality of Service (Q.o.S.) traffic profiles, security provision, support of different user profiles, distance-based services/applications. The players will be similar but they will have a different role. Infrastructure providers providing fast packet switching, native multicast and differentiated services support. Service providers building logical networks, and exchanging cost information among them based on destination address, traffic profile and congestion conditions. Finally users, encompassing both narrow and broadband and following both client-server and peer-to-peer models.

**Future Satellite Broadband System Targets**

The main improvement targets identified for future broadband systems can be summarized as:

- Improve satellite efficiency by: a) Efficiently integrate multicast and unicast capabilities, b) Increasing system performance by at least a factor \( \eta = 50 \) in terms of bit cost and capacity compared to today systems.
- Easy system re-configurability by: a) Matching system design to the packet traffic nature, b) More flexible, efficient and faster resource allocation.
- Improve future-proof integration with terrestrial networks by: a) Simplifying satellite network functionalities, b) Following standardized network management approaches, c) Adapting easily and efficiently to evolving terrestrial standards.
- Allow for low-cost user terminals by: a) Developing Low cost front-end, b) Optimized physical layer/MAC, c) Common terrestrial mass-market technologies, d) Exploiting standardized solutions.

**Reference Architectures**

Although the scope of the paper is not to define a specific satellite system, it is felt important to provide a system perspective and to identify system-engineering approaches that are suited to support future system requirements. Three basic “standard” architectures for broadband systems are retained:

- Distributed bent-pipe satellite Internet access
- Meshed type of regenerative satellite network for professional users
- Meshed type of regenerative satellite network for backbone connectivity

**Distributed Access Network**

The distributed broadband access network is supposed to provide high-capacity point-to-point and multicasting services for ubiquitous Internet access to sparse users. A multistar network topology with few gateways providing ground network access points (IXP) to a very large community of small user terminals is assumed. On the user link side narrow unicast beams and (linguistic type) of broadcasting beams are simultaneously present. User terminals aggregate just one or few users (Internet) traffic as a consequence unbalanced forward/reverse link traffic is generated. A bent-pipe satellite payload architecture is preferred for simplicity and to ease system evolution support.

For this architecture depicted in Fig. 2.1 the main improvement axes identified are: a) Large number of narrow Ka-band user beams to increase unicast system capacity (from today 40-60 to 100 or more beams), b) Few high-throughput (Ka or Q-band) gateways in site-diversity configuration to reduce terrestrial segment cost and deployment time, c) Flexibility in gateway to beam connectivity, d) Satellites (co-located) clustering to allow for capacity growth, e) Seamless highly efficient combining of multi-cast and unicast, f) Adaptive coding and modulation for high-capacity unicast, g) Powerful FEC and cache technologies for multicast, h) Low EIRP terminals I) Optimized MAC and resource allocation algorithms.

The target is to get a single GEO satellite system capacity in the range up to 50 Gbps.

![Fig. 2.1: Satellite distributed access network](image)

**Professional User Network**

The professional user network is a satellite broadband network that is intended to support different classes of professional users. This leads to a meshed topology with a multitude of ground access points. A set of earth stations classes will support the typical range of traffic required by the professional community. The main distinct characteristic of this architecture is the capability to easily build Virtual Private Networks for corporate applications supporting with high security intranet and videoconference applications. This will be provided on top of more conventional access to Internet Exchange Points (IXP) common to the distributed access network. In this case the inbound/outbound traffic is expected to be more symmetric and a packet (regenerative) on-board processor is required to efficiently support the meshed type of configuration. A block diagram of the network is
The main improvement axes identified so far for this network are: a) Increased number of Ka-band user beams to increase system capacity (from today 40-60 to more than 100), b) Cluster of satellites with short distance ISL for capacity growth and long-distance ISL for satellite GEO constellations, c) On-board packet self-routing, d) MPLS-type of networking for seamless integration with terrestrial networks, d) Optimized MAC and resource allocation algorithms, e) Adaptive coding and modulation for high capacity unicast. The target is to get a single GEO satellite system capacity in the range of 50 Gbps.

Although the number of satellite beams required in this case may be limited compared to the access network, the high-rate to be supported calls for the exploitation of Q-band with site diversity. Satellite capacity in the order of 100 Gbps or more is likely required to economically support this high-speed links.

**Networking Issues**

Future satellite systems shall provide an efficient support of current and future applications. Therefore, the system design shall be optimized for the traffic characteristics (e.g. client-server and peer-to-peer application models, packet nature, burstiness, variable packet size, QoS constraints, different levels of traffic aggregation and self-similarity). Future broadband satellite systems shall provide a seamless integration with future terrestrial networks. In particular, this calls for Quality of Service provisioning, native multicast support, allow multiple logical networks for different service providers (Virtual Private Network support), easier support of terrestrial protocol evolutions. The technical improvement axes identified so far are: a) MPLS-type of architecture avoiding too complex payloads by moving complexity towards the edges of the satellite network, and providing improved network performance and scalability jointly with easier support of terrestrial protocol evolutions; b) Optimized radio resource allocation techniques for up-link and downlink taking into account traffic QoS constraints and channel dynamics; c) Efficient MAC protocols for packet traffic on reverse link optimally combining contention and reservation techniques.

**Fig. 2.3: Backbone connectivity network**

MPLS-type (edge) Networking

The main driver behind the MPLS-type of networking is to bring processing towards the edges avoiding for instance real time routing within the network. This technology is currently finding large support by terrestrial networks and it will allow achieving an important number of features such as: a) Independence of services (a label is added in front of all packets), b) QoS of aggregated flows (e.g. differentiated services), and not on a per-flow basis, c)
Allow mapping of multicast trees onto Label Switched Paths (LSP), d) Scalability to support thousands of VPNs, e) Traffic engineering, i.e. routing traffic based on a number of policies (constraints). This technique can be crucial for the integration of satellite networks with the terrestrial ones as it will allow to route traffic on a more intelligent way.

![Diagram of network architecture with MPLS](image)

**Fig. 2.4: Network architecture with MPLS**

A MPLS-type of architecture as the one shown in Figure 2.4 is proposed to be used as well within the satellite network domain where the edge router functions are implemented on-ground [1].

### Optimized Radio Resource Allocation

The maximization of radio resources utilization on the uplink and downlink of the satellite networks gets more and more involved when dealing with packet data networks involving hundreds of beams and a multitude of users generating very bursty and unpredictable traffic. The new radio resource allocation algorithms shall take into account the packet nature of traffic and its QoS constraints, the adaptive frame duration of MAC, and the adaptive user information rate of the physical layer. Concerning the forward link, the Radio Resource Allocation optimization for adaptive coding and modulation represents an area of important research. This topic is very hot in the 3G terrestrial mobile networks arena [2] but has yet to be tackled for broadband satellite. De-centralized radio resource allocation algorithms shall be addressed in order to counteract scalability problems at the control unit and extensive radio network planning.

### Efficient MAC

The performance of the return link MAC will depend heavily on traffic characteristics: client-server and peer-to-peer application models, packet nature, burstiness, variable packet size, QoS constraints, different levels of traffic aggregation and self-similarity. Initial investigations have shown the high potential of asynchronous contention techniques (e.g. Spread Aloha) to reduce the end-to-end delay and improve throughput efficiency for lowly aggregated bursty traffic sources (e.g. Web). The end-to-end delay can be reduced because there is no need for capacity request and confirmation on a packet-by-packet basis, and the throughput efficiency can be improved by high-performance FEC. Other areas of investigation are related to the combination of contention and reservation techniques for traffic profiles presenting medium and high levels of aggregation, and the study of MAC efficiency combined with the resource allocation algorithms (i.e. taking into account variable frame sizes at MAC layer and adaptive user information rate at physical layer).

### Propagation Issues

Propagation phenomena play an important role in the design and performance of broadband satellite systems operating at Ka-band and above. Rain Attenuation at 20 GHz is 3 times higher than at 12 GHz. Cloud and clear air attenuation effects and ice-induced depolarization become noticeable. The key areas of investigation concerning propagation are: a) Models of fade dynamics for impairment restoration schemes; b) impairment mitigation concepts for high availability feeder links at 30 GHz and, c) Propagation models for Q- and V-band and long-term propagation statistics for model validation at these bands [3]. Preliminary studies of dynamic fade restoration using real-time meteorological data have shown that for a Ka-band downlink with a low fade margin (95% availability), several dB of savings can be achieved. It is expected that for systems with a higher link availability even more fade restoration can be achieved and studies to analyze the best trade-off between best restoration results and complexity of the system are currently being commissioned. In parallel, a COST Action (280) is investigating ways of optimizing the impairment mitigation schemes. Frequency re-use schemes are making use of orthogonal polarization for doubling the capacity of a particular satellite frequency band for a particular region. Rain and ice can lead to depolarization which leads to cross-talk (cross-channel interference). Rain-induced loss of cross-polar discrimination (XPD) is a concern for Ku-band systems but ice-depolarization (caused by ice needles in clouds) has been found to become more important at higher frequencies. In order to easily apply propagation prediction models, accurate electronic maps of radio climatic parameters such as rainfall rate, water vapor content etc., need to be available. ESA has, in collaboration with members of COST Action 255 developed such maps and made them available to ITU-R Study Group 3.

### Physical Layer/Radio Access

The physical layer plays a pivotal role in the advancement of satellite broadband capabilities. The main direction of efficiency improvement is related to
the classical modem power and spectral efficiency augmentation. A “static” capacity improvement is not satisfactory for unicast (point-to-point) applications, where the physical layer can be engineered in a way to efficiently cope with space-dependent interference conditions and time variant propagation impairments, which occasionally can generate quite deep fading conditions. Furthermore, to effectively cope with the extremely bursty packet traffic one should match physical layer design (coding, modulation, multiple access.) with application (access, traffic nature) and identify smart resource allocation strategies. The following improvement axes have been identified so far: a) High performance coded M-QAM modems, b) Slot-based adaptive coding and modulation (ACM), c) Optimized access and frequency and polarization reuse schemes, d) Reverse link optimized MAC/physical layer for access asymmetric traffic with low power UTs, e) Interference mitigation techniques at demodulator.

High-Rate Coded Modems
The above discussed need for improved physical layer power and spectral efficiency inevitably calls for the development of new modems that shall provide the following features: a) Powerful variable rate FEC (turbo) applicable to variable size signal constellations, b) High-speed high performance reconfigurable coded modulator/demodulator, c) Modulation and demodulation technique optimized for the nonlinear satellite channels d) Robust demodulator synchronization techniques.

It is becoming clear that next generation broadband satellite modems will have to support a much wider number of coding and signal formats in particular high-order modulations that are more fragile with respect to satellite or ground terminal nonlinear distortions. This calls for the design of variable rate codes (also matching the adaptive coding and modulation requirements) compatible with a host of signal constellations. Recent research results in the field indicate that this target should be feasible from the algorithmic viewpoint. VLSI technology progress pace also provides good confidence about the implementation feasibility. To speed-up design and optimization time there is also the need to devise and develop fast validation tools allowing investigating the end-to-end performance at low FER for coded modulations.

Adaptive Coding and Modulation
To efficiently cope with highly bursty traffic, location-dependent interference and time variant propagation conditions adaptive coding and modulation (ACM) is emerging as a very promising technology for terrestrial wireless networks. ACM appears particularly suited to support best effort unicast type of services as it provides variable bit rate links. By proper resource management techniques this bit rate variability may become hidden to premium users having special Q.o.S. requirements at the expenses of an average capacity reduction. Initial investigations performed by ESA on the ACM applicability to broadband satellite networks [4] showed very promising performance improvement for both the forward and the reverse link. The key is to overcome the current broadband satellites worst-case type of physical layer design, which is largely limiting the achievable system capacity. For the forward link approaches based on fixed power TDM (spread) beam carriers carrying variable speed downlink shared channels allow increasing the average beam capacity keeping the resource allocation problem within manageable boundaries. On the reverse link, ACM will allow a capacity increase while reducing the peak user RF terminal power required with large benefit for the terminal HPA cost.

The introduction of ACM physical layer in satellite networks is opening-up new R&D issues on the frame format and overall resource optimization strategy. Additionally, there are a number of R&D issues more related to the physical layer that need to be explored to make ACM practically exploitable by future broadband satellite networks.

Optimized Frequency Reuse and Multiple Access Schemes
The exploitation of very powerful FEC jointly with ACM and/or power control allows increasing the beam frequency reuse factor at the benefit of the overall system efficiency. Also the optimization of the multiple access technique allows exploiting better the spectrum and the available power. It is felt necessary to have a fresh look at the whole matter as the emerging physical layer techniques will have a major impact on the selection of frequency reuse and multiple access schemes. A combination of TDM(A) and CDM (A) techniques appears required to get more pushed performance. However the access design is heavily affected by the type of traffic to be supported.

Improved Reverse Link for Low Duty Cycle Traffic
The cost of user terminals is today largely dominated by the RF front-end cost. In particular the HPA power is a cost driver. Exploitation of ACM, access contention techniques like Spread-Aloha will open up the possibility to reduce terminal power not scarifying performance. Also the issue of low-end terminals supporting low size and duty cycle packet traffic will deserve further study and optimization as new physical layer solutions may results more appealing then the current one which were devised for bulkier type of traffic.
Interference Mitigation
The development of more power and spectral efficient modems will push the system frequency reuse so that intra-system interference mitigation techniques will become relevant. Although a very large amount of theoretical work has been done in the last decade in the field of interference mitigation more R&D activities have to be performed to bring the technology at the required maturation level. Pioneering ESA developments funded under TRP and later ARTES programs demonstrated the practical feasibility of adaptive interference mitigation technique to enhance CDMA demodulator performance [5]. However the bit rates supported by early prototypes are insufficient for the broadband application of interest here and techniques able to cope with ACM and more in general highly bursty traffic shall be looked at.

Payload Aspects
As stated in the introduction, the quantitative payload targets are quite challenging and are summarized below:
- Improve satellite capacity by a factor $\geq 10$
- Improve payload power efficiency by a factor $\geq 3$
- Reduce payload weight efficiency by a factor $\geq 2$
- Reduce payload bit/s cost by a factor $\geq N$

So that the overall figure of merit:
$$\Psi = \text{bps/(Hz} \times \text{km}^2 \times \text{kg} \times \text{W}_{\text{DC}} \times \epsilon)$$
shall be improved by a factor larger than 50-N.

The technical improvement directions are: a) Ka-band antenna and front-end supporting a large (>100) number of beams; b) Q-band antenna and front-end; c) Highly flexible and reconfigurable payload architecture supporting ACM; d) High throughput processors exploiting hybrid technologies for bent-pipe and regenerative; e) ISL for satellite clustering and interconnection (both RF and optical).

Antennas
Antenna architecture and technologies have long been the key to winning telecommunication satellite contracts. A clear vision and R&D roadmap in this area is essential in this domain.

Study of antenna requirements and candidate architectures
Different established or innovative antenna architectures can be considered to meet multimedia system requirements for the generation of multiple spot and/or shaped (e.g. linguistic) beams, possibly with reconfiguration to adapt to changes in coverage, traffic and/or propagation conditions. Possible antenna architectures include: a) One feed per beam parabolic reflector (or lens) antennas; b) One feed per beam shaped reflector antennas; c) Multiple feed reflector (or lens) antennas with overlapping feed clusters for each beam; d) Imaging reflector antennas magnifying a small array feed; e) Active phased arrays; f) Other innovative architectures. Each one can operate in the transmit and/or receive mode, in single or dual polarization and possibly with beam reconfiguration or beam hopping. A variety of beam forming schemes including low loss RF, multi-matrix, multi-port-amplifier, low level RF, IF, digital and optical, can be used to form the beams of these antennas.

In addition, for transmit antennas, architectures are strongly constrained by the DC to RF efficiency performance of the power amplifiers associated with the antennas, which depends on their mode of operation (single carrier, multi-carrier, required output dynamic range) and their implementation (TWT or solid state). Finally, thermal control of the power amplifiers brings, in the transmit case, different complex constraints of heat evacuation, less present in the cooling of receivers.

Reflector antennas for spot beam: transmit-receive with one feed per beam

Currently planned multimedia payloads will initially use one feed per spot beam with adjacent beams generated by different reflectors. This leads to 3 to 4 reflector antennas for European or CONUS coverage receive functions and the same number on transmit. Because of aberrations, many more reflectors would have to be added for full Earth coverage.

The combination of transmit and receive antennas to produce identical footprints from the same reflector, possibly in dual polarization is a challenge. This can be addressed with (dual reflector) configurations with very long (equivalent) focal length over diameter ratio so that feed element spacing is large enough to accommodate complex feed chain hardware. This has been studied under ESA contract [6] and has been implemented for ITALSAT payloads. Frequency sensitive sub-reflectors can also be considered to separate the transmit and receive feeds and to cause under-illumination of the main reflector in the receive mode to equalize footprints.

Reflector antennas for shaped beams: one feed per beam

Generation of multiple contoured beams (linguistic or global) with or without propagation compensation features is critical at 20 / 30 GHz and above. Use of multiple (small) shaped reflectors mounted on a common frame is a possibility. Each reflector has one or a few feeds per beam. The profiles of these reflectors can also be evolved into a single larger reflector with compromise shaping. Polarization sensitive reflectors at Ka-band and above are more lossy and critical than at Ku-band, particularly for shaped reflector profiles. RF sensing for fine antenna pointing and compensation for thermo-elastic deformation of the antenna structure is a critical issue.
Reflector (lens) antennas: multiple feeds in overlapping feed clusters

Multiple spot generation from a single aperture on receive is not foreseen to be a major development issue (unlike in the transmit mode), and has been addressed under ESA contracts in the 80’s [6] (with a 3.7 meter reflector at 20/30 GHz) and revisited more recently for ESA and CNES [7] and under the EU programme MULTIKARA [8]. Multi-feed reflectors typically use in their focal region 3 to 12 feed elements per spot, most of them shared with adjacent beams (overlapping feed clusters) - potentially provide a viable solution. Unlike the one feed per beam designs, this type of configuration can also generate (overlapping) shaped (linguistic or global) beams, possibly in the orthogonal polarization. In the transmit mode, to optimize use of resources and possibly to compensate for propagation changes, innovative antenna architectures are required for optimum efficiency, power to beam allocation and possibly beam reconfiguration.

For generation of overlapped shaped beams these could be derivations from the ESA patented semi-active antenna multi-matrix architecture [9] adopted for mobile payloads (ARTEMIS, INMARSAT 3) to increase efficiency and channel to beam allocation flexibility, see for example Fig. 2-5 from [10].

Active phased arrays and imaging reflectors

Active phased arrays can also be considered. They have the potential advantage of graceful degradation and full Earth coverage. The number and size of elements strongly depends on the sidelobe requirements. If grating lobes are not allowed on the Earth surface, small element spacing (\(\lambda\)) is required and the number of elements becomes prohibitive. If sidelobe requirements are limited to the EU or CONUS coverage, then larger elements can be used. Since, however, all elements contribute to each beam, beam forming is more complex. One other key problem is the efficiency of linear multi-carrier solid-state amplifiers (<20%), or TWTAs (<30 %), particularly with the taper required to control sidelobes. Edge thinning of the array can allow limiting this taper. The key R&D requirement here seems to be the development of linear power amplifiers retaining good power efficiency over a dynamic range of 6 to 10 dB.

The same considerations apply to imaging systems, where single or dual reflector based optics transforms a smaller array feed into a full aperture image array. These systems have extensively been studied under the ESA AKUBA development [12]. One advantage of the imaging antenna is that the grating lobes of the feed array miss the (sub) reflector and do not appear in the field of view. This can allow to decrease somewhat the number of elements with respect to the direct radiating arrays but this is at the cost of a loss in EOC gain and, to keep sidelobes under control, the reflector must be oversized with respect to that in a focusing system. The same R&D requirement for high efficiency power amplifiers over a reasonable dynamic range is identified here.

Repeater

RF/IF Repeater Technologies

The following repeater technologies and concepts have been identified for development under the different ESA’s R&D research programmes (TRP, GSTP, ARTES):

High Order RF/IF BFNs

A very high number of beams (i.e. 100) at Ka band will be required to get the target user access system capacity. The number of feeds contributing to each beam will range from a few (i.e. 7) for multi-feed focused reflector antennas to many (i.e. 50 to 100) for imaging and DRA antennas. Also, it is expected that a fraction of the total number of beams (i.e. 10%) will need to be steerable, in order to allow a certain degree of on board beam coverage reconfigurability. If such BFNs could be proven to be feasible at RF or IF frequency, it would be possible to take the BFN functionality away from the on board digital processors, with the associated reduction on power consumption. The feasibility of such high order BFNs should be demonstrated by hardware...
development activities trying to demonstrate the limits on BFN nodes and frequency of multi-layer substrate technologies.

*Flexible* TWTAs

Recent measurements on Ku and Ka band TWTs have proven the feasibility of controlling the output power from a TWT by changing its bias conditions. At Ka band, 3 dB output power control has been measured with very little (3 to 4 percentage points), very little linearity degradation and 7 dB gain reduction. Even higher values of power control range might prove to be feasible. These measurements confirm the feasibility of a “flexible TWTA” concept, where the RF power is controlled by telecommand. The flexible TWTA is a straightforward way to implement on board flexible power allocation to beams depending on traffic. Flexible TWTAs would be applicable to simple antenna configurations using a single feed per beam. Also, flexible TWTAs would further extend the capabilities of Multiport Amplifiers.

**High Order Multiport Amplifiers**

Multiport Amplifiers is a well known technique that allows an efficient way to implement power amplification on board when the power being sent to every transmit beam can vary depending on traffic demands. One of the main problems associated with this technique is the need of keeping a good phase and amplitude tracking between the different HPAs in order not to degrade the beam isolation performance. This problem becomes more severe as the frequency of operation increases and it is quite serious at Ka band. Other associated problems are the need to implement adequate redundancy rings to substitute failed HPAs (associated loss and mass increase) and the need to perform on board MPA phase and amplitude recalibration (after redundancy reconfiguration and to compensate for ageing effects). Linearity performance of the HPAs is also an issue in the case of high traffic imbalance between beams. The HPA tracking problems can be very reduced if high order matrices (i.e. 16 x 16) are used. Higher HPAs phase and amplitude-tracking errors can be afforded for the same beam isolation degradation. Also, on board MPA recalibration can be much simpler, with less accuracy in the compensation required. Another advantage of high order MPAs is that the redundancy scheme can be simplified with the associated reduction in losses and mass. The Multiport Amplifier concept can be combined with the use of “flexible TWTAs”. Apart from further increasing the capabilities for efficient power flexibility, flexible TWTAs could be used as a way to compensate for the power loss associated to TWTA failure and as a way to adjust the amplitude tracking between HPAs. The feasibility of the high order MPA concept should be proven by hardware development activities. In particular, the demonstration of the large output power matrix (i.e. 16x 16) at Ka band is proposed, to demonstrate the feasibility of such complex structure with high power handling capabilities. Also, on board recalibration techniques at Ka band should be demonstrated and tested.

**Large Order RF/IF Switch Matrices**

Next generation broadband multimedia payloads with a very high number of beams (i.e. 100) will need the implementation of high order switch matrices for on board channel to beam reconfiguration. In the case of analogue payloads implemented using IF processors, very high order IF switch matrices will be required. The feasibility of such matrices is not obvious using current technologies (i.e. GaAs switches on multi-layer substrates). MEMS (Micro Electro Mechanical Systems) technology is currently under development in the TRP programme. MEMS technology would allow the implementation of very compact and low mass very high order cross-bar switch matrix architectures. The feasibility and achievable performance of such MEMS based switch matrix shall be demonstrated by hardware development.

**GaN SSPA Technology for Tx Active Arrays**

Transmit active arrays at Ku and Ka bands are very critical due to the low efficiency of SSPAs under multicarrier conditions, the associated thermal problems and the corresponding large mass increase to get rid of the generated heat. GaN technology is currently under development in Europe. GaN will represent a technology breakthrough due to different factors: Increased power density of up to 10 times the capabilities of currently used GaAs technology, better thermal resistance and almost three times higher maximum junction temperature for reliable operation. Also, GaN devices operate with high voltage bias (40 to 50 volts), allowing simpler and more efficient EPCs, maybe using the satellite regulated bus voltage. Due to these advantages, active array antennas at Ku and Ka band will become more interesting, with significant relaxation of the thermal subsystem or with increased RF power capabilities as compared with current GaAs technologies.

**Very Low Cost Packaging Technologies**

There is a strong interest in the reduction of recurrent manufacturing cost of on board solid state microwave equipment for telecom applications (i.e. LNAs, Up/downconverters, channel amplifiers, SSPAs,...) . Next generation broadband multimedia missions will require a high number of recurrent microwave equipment and the push towards lower manufacturing cost will be even stronger. Next generation advanced packaging technologies are currently under development.
in Europe (i.e. flip-chip, 3D packaging, collective wiring...). These new technologies, will allow significant manufacturing cost reductions due to several factors (no wirebonds, batch manufacturing of many modules...). The modules built using these new technologies will have a very repeatable performance, of interest for many applications, i.e. active array antennas.

**Equipment for Q band Front-end**

Q band has been proposed for gateway links in satellite based access systems and for high speed point to point backbone trunking applications. Metamorphic HEMT (M-HEMT) technology starts to be available in European foundries. M-HEMT will allow improvements in noise figure and gain performance at Q band, as compared with currently available P-HEMT technology. Also, the use of next generation packaging technologies will be of high interest at Q band, due to the reduction of the effects of wirebond parasitics and the reduction of assembly and tuning costs. Activities on Q band equipment are currently planned in ESA’s R&D plans. Continuation of development efforts will certainly be required.

**Application of SiGe technology to LO Generation and Frequency Synthesizers**

Currently available SiGe technology in Europe allows the implementation of low cost mixed analogue/digital MMICs up to X band or even higher. This technology is best suited for low cost LOs and frequency synthesizers, offering a significant reduction of chip count and integration costs, together with very good low phase noise performance. Activities shall be started towards the development of a next generation of SiGe based LOs and frequency synthesizers.

**Filter Technologies**

In the domain of OMUX and power filters, developments are being proposed on the use of new materials and design techniques allowing lower losses, more compact designs, lower mass, higher number of channels and PIMP and multipaction free performance. The achievement of lower costs by minimisation of tuning efforts is identified by the use of improved simulation tools and more accurate manufacturing techniques. MEMS technology is also proposed for the implementation of reconfigurable filters (tuning of bandwidth, center frequency…) in IF processors.

**Digital Processors Technologies**

Today’s digital payload processors for communications applications (see Fig. 2-6), mainly narrowband transparent, largely benefit from microelectronics technology development allowing for very important contributions to the above-mentioned ψ factor. The medium to long-term evolution of broadband multimedia telecomunication satellite systems is clearly towards larger bandwidth, higher throughput, very fast dynamic resource management, large number of variable size beams. The main drivers for the microelectronics and digital processing domain are related to the increasing degree of processing requirements (throughput, bandwidth, performance, number of beams) of payload equipment, the need for flexibility and the need to provide this at very low power, size, mass and cost. Considering the above drivers, the main R&D objectives for the domain are summarized hereafter: a) Develop the capability of using deep sub-micron commercial technologies for space applications by improving radiation performance through design techniques only. This applies for total dose as well as SEE (SEU, SET, SEL). b) Low power, high performance signal processing algorithms and architectures and design techniques for Data path and signal processing applications, c) Usage of complex in-flight re-programmable FPGA despite the hazardous radiation environment System-on-a-Chip methodology, reusable IP-Cores and HW-SW-CoDesign

**Fig. 2.6: Typical digital payload functionality**

**Usage of Deep sub-micron commercial technologies and Improvement of Radiation Performance Purely by Design**

Many rad-hard foundries have left and continue to leave the space business, due to reduced demand by former military customers and lack of commercially interesting sales volumes. Therefore, ESA, based on the promising results of a small proof of concept study, initiated a TRP activity with the intention to develop a better understanding in the usage of deep sub-micron commercial technologies with improved radiation performance through suitable design techniques only. It is the intention to develop transistor level libraries with a small number of elements, which will simplify the re-targeting effort to different technologies. The result of these activities is a library, radiation hardened by design and available for free to European space industry. Future activities shall follow on to the previous TRP activity, taking into account the conclusions and recommendations and tackle the remaining problems. The use of these deep sub-micron commercial technologies featuring higher density, higher performance, lower power, lower cost, faster evolution, will result in considerable reduction of mass, size and
In particular the following items are required:

- Interface between analog and digital part of the system.
- Components to support these schemes are now at the development stage.
- These elements have been developed in the past to allow processing of signals with large bandwidth in low power CMOS technology.
- Further optimization on algorithm/ architecture level could improve power consumption between 10-20%.
- Additional improvement between 500-1000% is expected by moving to deep sub-micron commercial technologies.
- Exploiting full custom design techniques on transistor level an additional improvement of power-delay-products between 300-1000% has been experienced in the past with larger feature size technologies. This is in particular valid for regular high-speed blocks (frequency demultiplexers, frequency multiplexers, de-interleavers, interleavers and beamformers) where a large part of the power consumption is concentrated in communication payload processing.

Usage of complex in-flight reprogrammable FPGA despite the hazardous radiation environment

Flexibility and adaptability over the operation lifetime is a crucial issue. Large, reprogrammable, RAM based Field Programmable Gate Array (FPGA), with several million gates, might be part of a solution to provide more flexibility in payloads and avoid obsolescence during lifetime due to a change in a standard for regenerative payloads.

The feasibility of using these type of FPGAs in low speed regenerative digital payload processing blocks will be investigated and their limitations shall be analyzed. Critical issues to be solved are: a) in orbit reprogramming; b) protection against SEE (functionality and program memory (e.g. advanced TMR and memory scrubbing); c) power consumption, and d) design methodologies

The RAM based FPGA vendors have already begun to develop SEU mitigation techniques in order to make their devices usable in space applications. However, no systematic review of these design techniques has been performed so far. Many problems have been encountered due to technological reasons as well as due to design methodology deficiencies when FPGAs were used in the past.

Development of critical high performance, low power elements

Efficient Algorithms based on early parallelisation have been developed in the past to allow processing of wideband signals in CMOS technology. The critical components to support these schemes are now at the interface between analog and digital part of the system. In particular the following items are required:

- High performance, wideband, low power ADCs/DACs
- High Speed De-Interleavers at low power consumption
- High Speed Interfaces and Interconnects (ASIC-MCM, MCM-MCM, MCM-Board, Board-Board, …)

These elements are crucial for the system as they are limiting the performance of the overall system.

System-on-a-Chip methodology, reusable IP-Cores and HW-SW-Co-Design

Deep sub-micron commercial technologies offer very high integration levels and are able to fulfill the ever-increasing demands on performance in terms of processing speed, mass and power. With an increasing number of available gates on an Application Specific Integrated Circuit (ASIC), the functionality being implemented will move away from the use of traditional components to more advanced and complex systems within a single device. To develop such complex circuits the design methodology will have to change from being gate-level oriented to the integration of complex building blocks (reusable IP-Cores). The designers will have to rely on pre-existing building blocks with already verified functionality, with documentation and production test vectors being available, which have ultimately been validated on silicon. As a consequence also programmable processor cores (e.g. LEON), which in the past used to be on separate boards will be integrated together with other cores on a single device. This requires investigation into new areas such as hardware-software Co-Design, soft-core vs. hard-core issues, reusability issues of IP-Cores, verification, validation and debugging of such a complex system including hardware and software components.

High Throughput Processor for Future Bent-Pipe Broadband Networks

Past activities in the field of satellite broadband onboard processing have clearly shown the benefit of aiming at very ambitious targets - a direct processing of 250 MHz bandwidth in the early 90’s was one of such a target, which has now been achieved with great benefit for European Industry. Although previous pioneering R&D activities are fulfilling current multi-media payload requirements (i.e. Web/West, EuroSkyway), the handling of more beams triggers new challenges that at the present stage may seem far away or very difficult to reach. The proposed new activity aims at the detailed architectural study for a high throughput processor for future bent-pipe broadband networks. A bent-pipe solution seems in fact still the most attractive solution in the medium term for many operators who are reluctant to go in one shot to an on board processing solution, obviously the maximum degree of flexibility in terms of Gateway to beam connectivity is the background scenario.
Ultra-fast on-board processor for meshed packet networks

Since the early days of on-board processing satellite system architectures have followed many different approaches for switching and processing, in order to improve system performance on one side and to cover the widest possible range of user services within the same satellite system. From circuit switching to ATM all proposed approaches have been based on an isolated satellite switching network which would either provide satellite specific services or would interface with external terrestrial environment through gateways. The dramatic evolution of ground network towards packet based communications calls for a fully integrated approach where packet can transit the satellite network without any intermediate processing and more complex functionality are dealt with at the edge of the satellite network. Such an approach in the case of on-board switching would call for a pure packet based switching processor. Additionally, current proposed on-board processors with packet switching capabilities are fully regenerative thus greatly limiting the flexibility for the air interface and increasing considerably the complexity on-board. This issue becomes even bigger with the current trend of developing bigger and bigger platforms where more mass and power can be accommodated. For this reason it will be useful to investigate new processor concepts which are based on the idea to handle pure packet traffic on board but which does not require any processing on board for packet payloads. This transparency of the processor shall offer all the advantages of a bent-pipe satellite with the added capabilities of on-board packet switching.

High throughput representative demonstrator digital processors

Previous developments (e.g. INMARSAT 4) have shown that operators believe in the capability of a certain new technology only once a representative demonstrator had been built. This not only requires the developments of all the ASICs and MCMs but also the overall packaging scheme in order to convince that an estimated size, mass and power consumption can be met. This development is also critical in order to clear unforeseen obstacles from the development path and arrive at realistic schedule estimates. A representative high throughput demonstrator digital processor for both bent pipe and packet switching payload architectures shall be developed and implemented in order to convince operators concerning feasibility of such an undertaking.

Optical Technologies

Optical technologies can richly enhance data processing and communications systems undeniably in term of throughput. Furthermore, their impact on future satellite payload will be to improve the overall figure of merit, which includes mass, size, power consumption and cost, and also to enable functionalities for which there is no feasible electronic alternative (massive on-board signal processing like routing, correlation; ultra-accurate clocks). Foreseeable relevant applications encompass: a) high data-rate routing and switching; b) complex beam forming network; c) inter-satellite link; d) generic technologies (analog-to-digital conversion, optical backplane interconnects, optical power remoting, distribution of r.f. signals, wireless intra-satellite networks).

The reasons for the inclusion of optics in satellite payloads are to be found in their distinct advantages:

- parallel processing (Fourier transform, WDM);
- low propagation losses, permitting implementation of time delays;
- inherent EMI/EMC freedom and immunity, high isolation between ports (sometimes most important);
- very large available bandwidth.

In addition to these intrinsic properties of light, materials and technologies are rapidly evolving and maturing, providing also a high-performance interface between optics and electronics. All things considered, examples of areas of excellence for optics are:

**Optical Routing for Large Order Switching Matrix**

Optoelectronics technologies, driven by the communication market, have already demonstrated their capability in bandwidth insensitive, low insertion loss and high isolation routing. Optical MEMS provided the highest optical performance, and matrices of up to 32 x 32 elements are already available, reconfigurable within 10 ms. However applications of MOEMS technology and all the more scalability to 100’s x 100’s matrices have first to resolve substantial challenges: architecture (3D configurations can achieve highest orders but pose technical difficulties), reliability, packaging, space qualification. Some of these problems are almost unexplored up to now.

**Optical Beam forming network**

Different technologies (free-space optics, fibre optics, integrated optics) have been demonstrated for BFN of phased-array antennae. Up to now, the advantage of using Optical Beam Forming Networks has been questioned because of only moderate bandwidth and fan-out requirements in common systems. But as soon high-order BFN with variable steerability and large addressable bandwidth – that is to say flexibility and versatility – are required, optics is to be envisaged. The Agency is carrying out studies on antennae having a large number of feeds per beam / large area and a low power consumption. One suitable approach could be to use efficient Vertical Cavity Surface Emitting Lasers and mature Spatial Light Modulators. The philosophy of the technique is to address each individual radiating element
in a very large matrix and to superimpose beams using WDM principles. It has to be noted that the same principles can be implemented with Optical MEMS, proving even lower cost. Further activities shall address the demonstration of high-order, low power consumption BFN, and MOEMS networks.

**Optical Intersatellite Links**

The first ever Optical Intersatellite link was demonstrated in November 2001 between GEO Artemis and LEO Spot IV. Although based on 15-year old technology, it successfully proved pointing, acquisition and tracking, and 50 Mbps communication link. Currently, two technologies are envisaged: mature Nd:YAG at 1.064 µm with coherent homodyne detection, and SC laser (1.55 µm) boosted by an optical (fibre) amplifier to perform direct detection. Target performance is 10’s of Gbit/s, while 7.8 Gbit/s have already been demonstrated in lab (mostly with space-qualified devices for short-range (LEO-LEO) communication link). The critical issues lie in the received power and the pointing, acquisition and tracking. These constraints are less stringent for intra-orbit links, and make Optical ISL suitable for certain configuration of clustered satellites, with an expected data rate of the order of tens of Gbit/s [15]. In this context, an important further activity shall deal with weight and power consumption, as well as space qualification.

**Optical Intrasatellite Links**

In the intra-satellite environment, we investigate optical technologies at different levels: inter-chip (to permit real-time parallel processing architectures); optical backplane and optical networking. In this latter field especially, applications are being developed to increase the capacity of transmission. The concept of SPACEFIBRE is an extension of the SPACEWIRE standard in the intra-satellite links and on-board networking. The latter currently employs copper links for up to 400 Mbps, whereas SPACEFIBRE pushes the capacity to multi-Gbps, with substantial gains on weight. A complementary activity that shall be developed specifically concerns the harness reduction. Optical wireless transmission would replace the numerous copper wires dedicated to low data rate links distributed all over the satellite (e.g. network of miniature and autonomous sensors). This activity would also include power remoting.

**TERMINAL ASPECTS**

The user terminal technology development is key to the success of broadband satellite systems in particular for consumer or “prosumer” (between professional and consumer needs) applications. The following improvement axes have been identified: a) Low-cost front-end technologies for Ku/Ka-band (including steerable antennas); b) Optimised Physical/MAC layers for satellite packet services; c) Exploitation of low-cost caching technologies (edge casting) to reduce unicast traffic; d) Support of edge networking technology. For enabling cost reduction and stimulate competition new techniques and technologies shall eventually enter the standardization bodies.

**Advanced User Terminal Antenna Concepts**

**Terminal antenna requirements and architectures**

For fixed terminals, single (and multiple) feed reflector antennas are currently used for most fixed home and professional user. Improvement of the aesthetics of terminals calls for planar or conformal antenna solutions with costs comparable to those of reflector antennas. For mobile terminals, for communications on the move, from cars, RVs, buses, trains or aircraft, tracking and beam scanning must be implemented mechanically and/or electrically. Architectures expected to require further research include: a) Planar or conformal (transmit and/or receive) arrays for single beam fixed terminals; b) Multiple feed reflector (or lens) antennas for multi-satellite access from fixed user terminals; c) Beam steering arrays with mixed electrical mechanical scanning; d) Planar or conformal beam steering arrays with electrical scanning. Other innovative architectures in particular with global phase shifting (rather than on a per element basis) are being considered.

**Advanced antenna concepts for fixed user terminals**

Planar array single beam TVRO Ku-band antenna, for example based on multilayer designs [16] are currently on the market. Transmit/receive terminal antennas are not available and this is clearly an area of research, which will grow in importance for multimedia users. Terminals with multi-satellite communications capability already exist for TVRO and could well be used for multimedia satellites. Multiple feed or array fed reflector antennas can be designed to meet these requirements and toroidal reflector antennas [14] and lens antenna solutions [18], which potentially offer better off-axis scanning performance, are also being developed for multiple satellite use. Low cost transmit/receive feeds require a development effort.

**Advanced antenna concepts for mobile user terminals**

Several DBS receive-only terminals at Ku-band for cars, buses and aircraft are available on the market, but they are very bulky and cost several thousands of euros. Usually based on mechanical azimuthal rotation they can either have a fixed shaped beam [19] a mechanically
steerable beam [20] for electronic beam control [21] in elevation. Active phased array solutions have been developed for aircraft at Ku Band and at higher frequencies by Boeing [22]. It is believed that phased array configurations, active and even passive, with fully electronic beam steering cannot meet the low cost requirements of the car users. A breakthrough in the implementation of beam steering is required to achieve an affordable, and attractive product. Adaptive or retro-directive antenna design solutions are to be considered. For transmit / receive systems the terminal antennas can make use of dual frequency radiating elements, (or possibly interleaved elements) or of separate transmit and receive arrays. Dual frequency elements can lead to problems associated with scanning (electrical) and isolation, while the use of separate arrays results in a larger terminal.

Again, a breakthrough in beam scanning implementation is required together with innovative antenna architectures that minimize the number of components. Also, micro-electromechanical systems (MEMS) are being considered for phased array applications [23] where they have the potential for low cost manufacture of beam switching/scanning networks. With the asymmetric traffic requirements of Internet and multicast, the initial market demand might be for a primarily receive system with some limited transmit capability, possibly via an alternative path, e.g. GSM or L-band. Currently, a flat phased array antenna which can transmit in L-band and receive broadband data in Ku-band is under development [24]. Critical technologies required for low cost terminal antennas include: a) Dual frequency radiating elements and feeds; b) Innovative low cost array and beam steering architectures; c) Development of advanced technologies, e.g. photonic band-gap techniques, MEMS, for passive/active array antenna applications.

**RF Front End for User Terminals**

A very significant cost reduction of user terminals is necessary in order towards have commercially viable broadband multimedia satellite systems. Two main areas of improvement on the RF front end are the SSPA and LO synthesizer.

**Low cost SSPAs**

It is necessary to develop very low cost 30 GHz SSPAs giving RF power in the range 0.5 to 2 watt for the user terminal outdoor unit. Main cost drivers of these SSPAs are the GaAs MMICs and associated packaging. Currently, efforts are being made to optimize the SSPA design to take minimum chip area and to use new power optimized GaAs processes. Low cost packaging concepts are required that are able to operate at 30 GHz and with good thermal properties in order to handle high amounts of dissipated power. A planned ARTES 5 activity is going to address the development of low cost SSPA modules considering currently available technologies. In the future, the advent of GaN technology will allow the implementation of very small and therefore low cost SSPAs. GaN technology, together with the use of next generation advanced packaging and interconnect technologies will imply a breakthrough on cost reduction of user terminals.

**Low cost LO Synthesizers**

Low phase noise LO frequency synthesizers have also been identified as cost drivers for Ka band user terminals. SiGe technology can be used to obtain meaningful cost reduction of these synthesizers. This technology will allow the design of low cost combined analogue/digital circuits integrating in the same chip the VCO and PLL loop including frequency dividers.

**Baseband Technologies**

**Optimized Physical/MAC Layers**

For consumer/prosumer type of terminals the aim is to reduce the EIRP required for user terminals for given rate or to increase the bit rate supported for given terminal EIRP. Adoption of the enhanced coded modulations discussed before is certainly going in this direction in particular when combined with ACM techniques that has shown by internal ESA studies appear to largely reduce the HPA power requirements. Also for low-end low-rate applications an optimized multiple access scheme like CDMA may reduce the terminal EIRP requirements and the terminal user friendliness. Interference mitigation at the gateway will certainly help in reducing terminal EIRP, while interference mitigation in the terminal will improve satellite downlink resources efficient exploitation. MAC adaptation to the traffic nature will open up interesting improvement perspectives.

**Exploitation of Low-cost Caching Technologies**

Terminal caching technologies are pivotal to exploit the satellite multicasting capabilities to reduce the amount of unicast information to be transmitted thus improving the system efficiency. The incorporation of low-cost cache memory technologies in the user terminals for pushing multicasting exploitation will cause an important service cost reduction providing common information locally available at low-cost. The user can easily select his own profile to optimize the utilization of his cache memory. Local/remote interactivity will allow for seamless multicast and unicast service integration at the terminal. The cache technologies cost is falling thanks to terrestrial market explosion (video cameras, digital cameras, MP3) and satellite systems shall be designed exploiting this mass-market technology.
Support of Edge Networking Technologies
As mentioned earlier, edge networking is a key to simplify the satellite networking functionalities. This approach however requires an increased number of interworking functions to be performed by the terminal itself. Among others, mapping and aggregation of packet flows into Label Switched Paths (LSPs). The terminal shall support of standard protocol stacks and type of equipment (e.g. standard IP edge routers or ATM edge nodes). Edge nodes shall interface with user terminals via standard interfaces.

Digital Technologies
A demonstrator terminal, fully integrated shall prove the feasibility of implementing the new features such as edge networking, adaptive coding and modulation techniques, interference mitigation techniques, caching techniques discussed above. This will require the exploitation of the state-of-the-art VLSI technologies and caching techniques.

CONCLUSIONS
This paper contains a preliminary review of promising technological avenues for improving the performance of broadband multimedia systems in terms of service cost, flexibility and adaptability to terrestrial networks evolution. It has been shown how the challenging improvement targets set forth in the introduction require a multi-disciplinary technological development effort. In order to maintain, and possibly enhance, the satellite complementary role with respect to terrestrial infrastructure, ESA is currently engaged in the investigation and the development of the most promising techniques and technologies able to enhance European and Canadian industry competitiveness in this strategic field.

REFERENCES
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