Concepts and Technologies for a Terabit/s Satellite

Supporting future broadband services via satellite

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***Abstract*— In this paper we investigate the next but one generation of fixed satellite systems and the technological challenges that face this generation which we define as operational by 2020. Various technologies and architectural concepts are presented with a view to identifying the most promising to pursue. The dimensioning of the system has demonstrated that several new technologies are appropriate for development before such a satellite system is feasible. Work is continuing to investigate these in more detail but we feel there to be no technology show stopper for a Terabit/s satellite by 2020.**

Keywords-satellite communications; broadband, advance systems Internet over satellite.

I. INTRODUCTION

In this paper we investigate the next but one generation of fixed satellite systems and the technological challenges that face this generation which we define as operational by 2020. The current generation of large geostationary satellites are characterized by a capacity of up to 10Gb/s and are about 6 Tonnes in weight. They have historically predominately operated in C and Ku bands but with Ka band now coming into use and in general are multi beam with less that 100 beams per satellite. Just on the horizon is the next generation which will take the capacity up to 100Gb/s but with similar sized satellites making use of a larger number of beams and more complex payloads. These will take us through to 2015 or beyond; but what comes next? Here we look at this following generation of satellites and set ourselves the challenge of a further order of magnitude increase in capacity to a Terabit/s satellite [1]. The paper will concentrate on a single geostationary satellite but we recognise that there could be other solutions; for example constellations or multiple smaller co-located (clusters) satellites. We see the drive for higher capacities in three areas; Data Relay, Broadcasting and Broadband Access. Each has its own and different specialised requirements for the satellite. Herein we will concentrate on the third of these; the Broadband Access satellite for the 2020's.

Broadband access to the internet is a growing service area and satellite is ideally placed to deliver such services to areas that are uneconomic for terrestrial systems. Recently Cisco have predicted internet demands of 104 Peta bytes per second for Europe by 2012 which is 10 times the internet traffic in 2007 with such growth to continue for the rest of the decade. By 2013 an average European household bandwidth will be 500GB/month. On average this would require in excess of 30Mb/s for domestic users wherever they are. This represents a considerable increase on the Digital Plans adopted for European countries currently which aim at 2Mb/s for all. Terrestrial systems will not be able to economically cover the whole population base at these rates, even with LTE-A becoming the endemic mobile standard by this timescale, and thus broadband by satellite on a Europe wide basis will be a key provider of the future internet architecture in order to avoid the so called Digital Divide. It is also forecast that following the migration of speech services from fixed to mobile, Broadband is likely to follow suite in the latter part of the decade increasing the importance of satellite delivery to ensure full coverage.

Until recently, Fixed Satellite Service (FSS) satellites have so far been developed such that they can flexibly meet a wide range of service roles thereby covering diverse market places. Such systems are not optimum for broadband services and tended to be power limited but are increasingly also becoming bandwidth limited. Their ability to provide services at comparable cost/bit to terrestrial systems has been technology limited due to this lack of optimisation. However they have the advantage of wide coverage and this will persist for broadcast and multicast services but can also be used to good affect for low density user services for example in rural areas. The cost/bit comparator still exists and whilst rural users might expect to pay a small premium it cannot be too far out of line with terrestrial costs. In the

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short term the challenge is to reduce the cost/bit by an order of magnitude and in the longer term (2020) by two orders of magnitude. This paper concerns the technology advances needed to bring this about and leads us to a Terabit/s satellite by 2020 by adopting a bespoke broadband optimised design.

There are some issues which are immediately apparent. As the demand for satellite capacity has steadily increased the limits of traditional Ku band satellites due to congestion of orbital slots is evident as well as the limitations in the spectrum available to cope with predicted demands. In addition these satellites are built to cover wide geographical areas and hence have limitations to support flexible distribution of bandwidth that will be needed for a European Broadband satellite application. These limitations force us to look at higher frequency bands of Ka and above where it becomes easier to realise a larger number of spot beams on board the satellite and hence via frequency reuse achieve the capacity requirements.

Broadband demand is being met terrestrially by local loop systems such as ADSL 2 but as the requirements exceed 10Mb/s only around 40% of households in the UK will be able to be serviced. Fibre to the Home (FFTH) across Europe is patchy and unlikely to be the answer for 20 to 30 years if ever in some areas. Wireless terrestrial is also at the mercy of spectrum allocation which is non uniform and LTE-A systems to deliver in excess of 30 Mb/s across cells is still a long way off and may never reach the rural areas. Thus the market in Europe indicates that there is demand for satellite services of this type. A study by IDATE in 2009 [2] considered the households that were not covered by broadband considered as the unserved market as follows;

- Western Europe 5.2 million
- Baltic countries 0.6 million
- Eastern Europe 6.6 million
- North Africa 18.0 million

In addition, there have been three studies of market demand conducted recently (2009);

1) Northern Sky research [3]
   A ten year forecast which indicates that by 2018 satellite broadband will reach 1.2 million subscribers in Europe.
2) SES ASTRA study [4]
   A detailed country by country study which includes the increased take up of terrestrial broadband and indicates addressable satellite markets not being served by terrestrial in low/median and high by 2020 as 0.44/0.85/1.25 million.
3) Eutelsat study [5]
   Indicates that the addressable market for satellite broadband will reach 3.5 million by 2018.

The above studies all indicate a significant market for European satellite broadband in terms of households that will not be served by terrestrial means even given the increase in terrestrial provision. If we include North Africa in the coverage the market becomes very large.

The remainder of this paper is structured as follows,

- Spectrum availability – assessment & implications;
- System architecture and satellite beams;
- Gateway/UT & beam parameters;
- Power and bandwidth requirements;
- Satellite Power Assumptions;
- Adoption of the Smart Gateway Concept;
- Achievable Performance;
- Other studies;
- Making the Terabit/s satellite a reality;
- Conclusions.

II. Spectrum Availability

As we have already mentioned it can be demonstrated that Ku band does not possess sufficient spectrum for a Terabit/s satellite and so we will concentrate on both the Ka and the Q/V bands which have FSS allocations.

a) Ka Band

Exclusive bands for satellite are –19.7-20.2 and 29.5-30 GHz that is 2x 500 MHz across the European Union (EU) and this is proposed for use by both HYLAS and Eutelsat Ka-SAT. Under European Electronic Communications Committee (ECC) decisions [6], [7] these bands are exempt from individual licensing for low eirp terminals (<50dBW (recently updated in the UK to 55dBW) and in some countries 60dBW). All other parts of Ka band have shared primary frequency allocations and thus would be subject to coordination at particular earth station sites. The band 20.2 to 21.2 GHz is a dual military use band with the possibility of reuse but this would be difficult to coordinate across Europe and hasn't been considered herein.

Up Link

27.5-29.5 GHz shared with Fixed Services (FS); some portions auctioned in UK requiring coordination.

24.75 -25.25 GHz in ITU Regions 2/3 but not Region 1.

Hence 2.5 GHz is available but with restrictions.

Down Link

17.3-19.7 GHz shared with Broadcasting Satellite Service (BSS) feeder links and also FS with many terrestrial links operating across EU needing coordination and maybe restricted to rural areas.

21.4-22 GHz in ITU Regions 1/3 shared FS/Mobile/BSS. Hence 3 GHz is available but with restrictions.

The current EU interest regarding the use of Ka-Band are currently under review and a draft report indicates the various interests in the European Conference of Postal and Telecommunications Administrations (CEPT) [8].

b) Q/V Band

There are no exclusive bands for satellite (FSS) here and thus all this spectrum is subject to coordination with other users, even the User Terminals (UT's). This is not a show stopper but complicates the business model.

Up Link (V)

42.5-43.5 GHz is shared with FS/Mobile/RA. Portions auctioned in UK (3 operators paired with above);
47.2-50.2 GHz is shared with FS/Mobile but with military and Outside Broadcast restrictions;
50.4-51.4 GHz is shared with FS/Mobile but military restrictions in some countries.

Down Link(Q)

37.5-39.5 GHz is shared with FS/Mobile/Space research. This band is extensively used by FS.
40.5-42.5 GHz is shared with FS/Broadcasting/BSS/Mobile. Portions of this band have been auctioned in UK (3 operators) and in some other countries, requiring coordination.

Hence 5 GHz available for the uplink and 4 GHz for the downlink but with restrictions and coordination is needed. CEPT ERC/DEC has provisions in some parts of the spectrum and in some countries priority is given to military use.

c) Spectrum Summary

The spectrum for an EU wide satellite system is very complex with country to country variations and only 2 x 500MHz exclusive in Ka band. It may be that satellite operators have failed to lobby adequately for these bands and now some action is needed especially in Q/V bands with both the regulators and in WRC to restore sufficient spectrum for future systems.

III. SYSTEM ARCHITECTURE AND SATELLITE BEAMS

In order to achieve the Terabit/s satellite capacity we will need to use advanced air interfaces and frequency reuse beams from the satellite. We will assume basing the air interface on the current DVB-S2 standard and suggest later any modifications that might be required.

The DVB-S2 Standard [9] and its associated Guidelines document [10] give parameters for the air interface.

We have chosen to adopt a filter roll-off factor of 0.2 to represent modern equipment performance.

For system architecture analysis purposes the parameters given in Table 1 have been selected as a starting point recognising that Adaptive Coding and Modulation (ACM) and Fade Mitigation Techniques (FMT) using other mod codes may be useful in combating rain fades.

TABLE 1 WAVEFORM PARAMETERS CONSIDERED

Modulation	Eb/No (dB)	C/N in BW	spectral efficiency (b/s-Hz in BW)	FEC
16 APSK	6.4	10.8	2.75	5/6
32 APSK	8.1	13.5	3.43	5/6

Frequency reuse in the multi-spotbeam satellite antenna is commonly taken as either 3 or 4 colour with higher values (beyond 4) having diminishing returns. Current generation satellites at Ka band produce of the order of 80-100 beams to cover Europe.

In order to obtain an initial and preliminary estimate of the numbers of beams we have assumed either 16 or 32 APSK being in common use by 2020, with 3 and 4 colour reuse in the user beams occupying approximately 3 GHz of bandwidth at Ka band and take advantage of the fact that the gateway beams are significantly geographically separated permitting the use of the entire 4 GHz of bandwidth at Q/V band in each beam.

a) Limitations of beam number analysis

It is important to note that such an initial estimate is based upon bandwidth, spectral efficiency, frequency reuse and polarization reuse only and factors such as spacecraft payload, EIRP, C/N and C/I have been neglected in this initial assessment, as it is aimed at scoping the number of beams rather than determining a definitive solution. Thus, we have performed an initial set of calculations using a range of frequency reuse colours and polarizations with the stated spectral efficiency in order to assess various architectures. Furthermore the initial analysis considers uniform traffic loading in each beam and a practical system may require a higher number of beams than those suggested to account for non-uniform traffic whilst achieving a Terabit/s throughput.

IV. GATEWAY/UT & BEAM PARAMETERS

For an internet access service a star configuration into a gateway is to be preferred and so we now look at system architectures which have separate beams to User Terminals (UTs) and to Gateway Earth Station. We consider that the Gateway Earth Station will cover several UT beams and thus there will be fewer of them but they will carry greater capacity and hence need to be allocated more bandwidth.

a) Mixed Ka and Q/V solution

We have found that an initial architecture that employs the use of Q/V bands on the feeder links and Ka band for the UT links [11] appears to offer the best throughput. It should be noted that at Ka-band under existing regulation only 500 MHz would be in the exclusive satellite band and thus some of the UT's would need to coordinate. This is not seen as a major hurdle but regulators would need to adopt an on-line fast-track scheme.

b) UT beams

The bandwidth available is 2.5 GHz on the uplink (all bandwidth allocated to the user link as the feeder link is at Q/V band) and potentially 3 GHz on the down. For 2.5 GHz, three frequency reuse colours and 32 APSK the initial numbers of beams is found to be around **175** (or 88 with dual polarization) recognizing the limitations of our analysis as given in III a) above.

c) Gateway beams

The bandwidth available is 4 GHz on the up link and 5 GHz on the down link. For 4 GHz and the conditions above and using one frequency colour (possible because of large geographical gateway beam separation) the number of beams is 38 (or 19 with dual polarization) recognizing the limitations of our analysis as given in III a) above.

As already mentioned there are shared services in this spectrum and thus the siteing of the Gateway Earth Stations would need to be considered on a country by country basis.

Use of 16APSK would increase the number of beams substantially. Figure 1 to Figure 3 depict initial beams configured for European coverage recognizing the limitations of our analysis as given in III a) above.

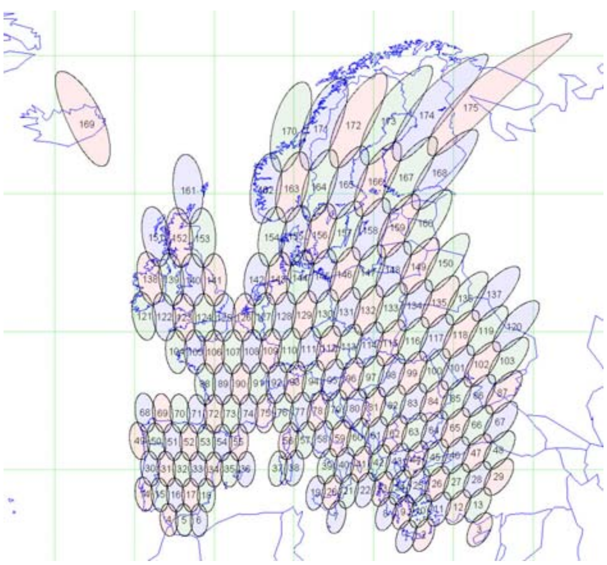

Figure 1. Representative 175 single polarised user beams over Europe

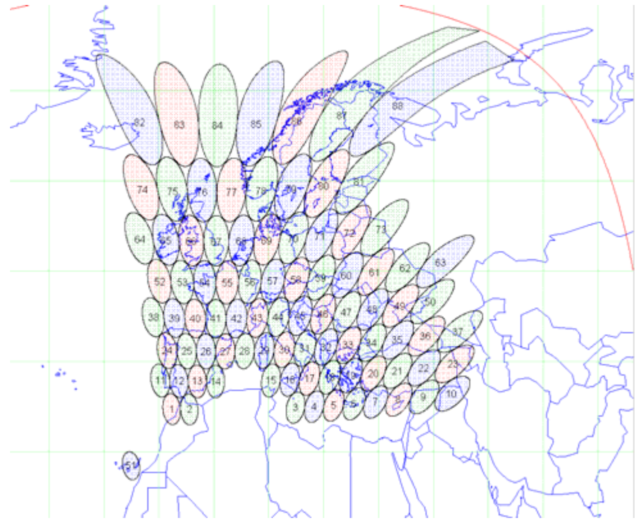

Figure 2. Representative 88 dual polarised user beams over Europe

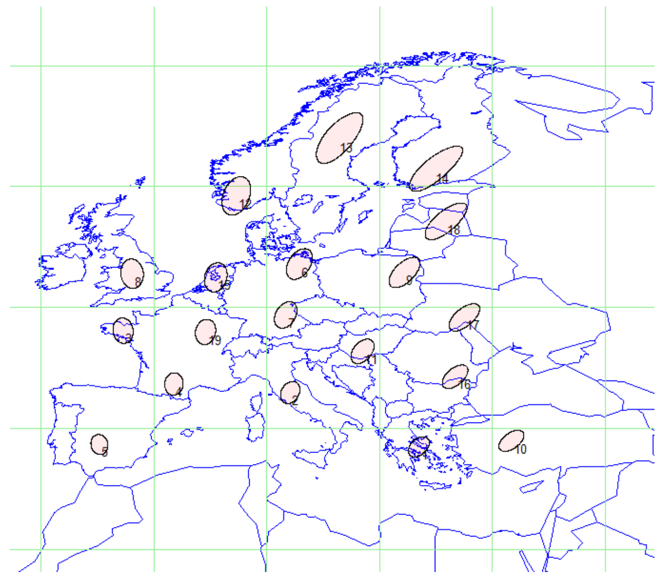

Figure 3. Representative dual polarised 19 beam Gateway configuration over Europe

V. POWER AND BANDWIDTH REQUIREMENTS

Here we look at power/bandwidth requirements for the Q/V-Ka band architecture in order to get some initial assessment of its feasibility. We will make some initial assumptions.

Pending further study of the relationship between beams and antenna size we assume that we have a 5m foldable reflector antenna for the UT side and a 2.5m reflector antenna on the Gateway Earth Station side of the satellite.
Assuming 65% efficiency on both we have;

Gateway Earth Station Band:

Gain Sat Rx (50 GHz) =60.5 dBi

Gain Sat Tx (40 GHz) =58.5 dBi

For a payload temp of 400K the G/T=34.4 dB/K

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For a 15 W transponder output power the downlink eirp =70.3 dBW or 67.3 dBW at Edge of Coverage (eoc).

UT Band:

Gain Sat Rx (30GHz) =62 dBi

Gain Sat Tx (20GHz) =58.5 dBi

For a payload temp of 400K the G/T=36 dB/K

For a 50W HPA output power the transponder downlink eirp =75.5 dBW or 72.5 dBW at eoc.

For the forward link we assume a bandwidth of one GHz and in the reverse link we assume that 40Mb/s users with 32 APSK would need a bandwidth of 10 MHz.

Ka band UT:

Baseline UT is taken as a 0.75m dish with a noise temperature of 150 K and G/T of 20.3 dB/K.

The transmit EIRP will be taken as 55 dBW representing the current allowable non coordinated value agreed in many EU countries. Thus the SSPA would be 8.8 W.

Q/V GATEWAY EARTH STATION:

The baseline Gateway Earth Station is taken as a 5m dish which has a transmit gain of 66.5 dBi at 50 GHz and a receive gain of 64.5 dBi at 40 GHz. On the transmit side with a 2 dB feeder loss and 16W transmit power the eirp is 76.5dBW.

It should be noted that moving to a larger diameter Gateway Earth Station antenna would increase the Gateway Earth Station costs significantly (50 GHz operation) and the extra performance is not necessarily needed as the system is self-interference limited and not thermal noise limited.

We assume a G/T of 38 dB/K which represents an overall earth station noise temp of 450 K which seems reasonable in this band.

Total rain fading across Europe has been evaluated using the ITU-R model assuming an availability of 99.9% for the Gateway Earth Station and 99.7% for the UT's thus for single site worst case conditions the potential margins required are given in Table 2 along with typical Free Space Loss figures.

TABLE 2 POTENTIAL FADING ACROSS EUROPE

Frequency (GHz)	99.7 % (dB)	99.9 % (dB)	FSL (dB)
20	3	6	210
30	11	15	214
40	15	20	216
50	23	27	218

Of course not all Gateway Earth Stations and UT's will be faded at the same time and to get a better idea of the overall degradations we include the spatial variations of the rain and to determine the average system reductions in capacity.

For the purposes of this feasibility analysis we have chosen to examine the system capabilities under clear sky conditions and have assumed that rain faded conditions can then be addressed by appropriate application of FMT such as ACM. This initial working assumption will be studied further to assess its validity.

VI. SATELLITE POWER ASSUMPTIONS

The trend is to larger satellites with upwards of 10 tonnes being possible in 2020. However the longer term power limits of the payload are constrained by the volume available under the launcher fairing. With current series of launchers this is estimated to constrain the payload power to circa 20KW EOL [12]. Thus it is important to ensure that the number of beams dimensioned in the previous section can be suitably fed by HPA power within the satellite payload power limits for the forward and return downlinks.

VII. ADOPTION OF THE SMART GATEWAY CONCEPT

The Smart Gateway architecture employs a number of Gateway Earth Stations which are inter-connected with terrestrial deeds to form an agile routing of feeder link data that can be used in a diversity manner to combat fades on the gateway to satellite links [13]. The approach is depicted in Figure 4.

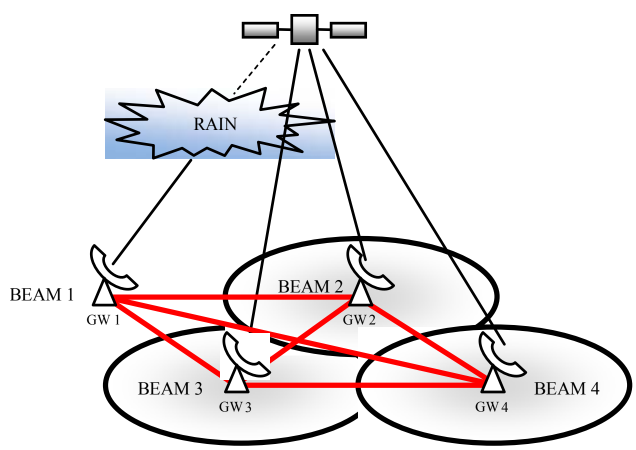

Figure 4. Smart Gateway Concept

According to this concept:

- Existing gateways are inter-connected to form a terrestrial network.
- Each user is serviced by a number of gateway feeder links.
- In the event of a gateway experiencing outage or reduced capacity, some or all user traffic can be re-directed terrestrially to any one of the remaining gateways, in any spot beam.

Advantages:

- Reduced cost → no additional gateways/antennas.
- Diversity gain → many more gateways, greater inter-site distance.
- Efficient gateway usage → all gateways simultaneously operational.
- Efficient resource usage → can utilise capacity wherever it exists.
- Implicit fault tolerance, opportunity to load balance and improve throughput.

Disadvantages:

- The allocation of gateway feeder link capacity to users is a critical function.
- Control/Switching algorithms required to detect capacity fluctuations and make traffic allocation decisions to achieve aims.
- A high degree of synchronisation in the gateway network is required.
- Some level of 'intelligence' is required in the Network and terminals.

Smart Gateways can potentially be used to avoid interference and to minimize the propagation effects for each gateway. Initial studies have shown this concept can be useful and simulations performed using traffic / weather statistics assumptions have demonstrated the advantages of the concept. The concept is attractive but as yet still immature and needs further consideration, especially at the payload level. This initial work will be followed up with improved assumptions to investigate load balancing as well as switching issues.

VIII. ACHIEVABLE PERFORMANCE

Based upon the parameters detailed above the performance was assessed under clear sky link conditions for the forward and return links.

The combined C/(N+I) for the forward link was 14.6 dB for a co-channel C/I of 20 dB. This represented a margin of 1.1 dB over the required value of 13.5 dB.

A key limiting factor here is the C/I of the satellite antenna beams. This needs to be investigated in more detail.

In the forward link it may be appropriate to adopt beam hopping as this has the potential to improve the downlink C/I (adjacent channel) to around 25dB but again this requires further studies.

The combined C/(N+I) for the return link was 15.0 dB for a co-channel C/I of 20 dB. This represented a margin of 1.5 dB over the required value of 13.5 dB.

The EoC eirp has been estimated assuming 100 x 10 MHz simultaneous carriers and sharing the power between them.

As for the forward link the C/I of the satellite antenna dominates the performance. Use of beam hopping on the return link would be more complicated as the UT's would need to synchronise with the on board system. Hence it would be more useful to study in detail the aggregate effect of the sporadic transmissions on the return link to see if the C/I is in fact improved. This requires figures on beam loading and activity ratios. On the Gateway Earth Station side the situation is improved due to beams at the same frequency being spaced further apart.

Here again we see a need for further consideration on how to improve the co-channel C/I on the satellite antenna.

IX. OTHER STUDIES

Other studies have been undertaken and include:-

- Forward Link: to assess the ACM operation in Ka-band and investigate the potential for new MODCODs for rainy regions, using simulated precipitation field models (see figure 5);
- Return Link: to investigate ACM on the return link (DVB-RCS NG like) at Ka-band;
- Evaluation of the beam displacement due to satellite movements & resulting C/I degradation with the potential to exploit terrestrial mobile hand over concepts to combat the effect of beam movement;
- Evaluation of C/I in the return link with appropriate traffic patterns and utilisation figures;
- The potential of higher order modulation and coding;
- Further evaluation of the feasibility of the Smart Gateway approach and its impact on the payload and system architectures;
- Accurate assessment of the system availability using a space time-channel model which facilitates
  - Test of routing strategies for smart gateways
  - Evaluation of the effectiveness of ACM on the users links
  - Possible minimization of the required payload flexibility.

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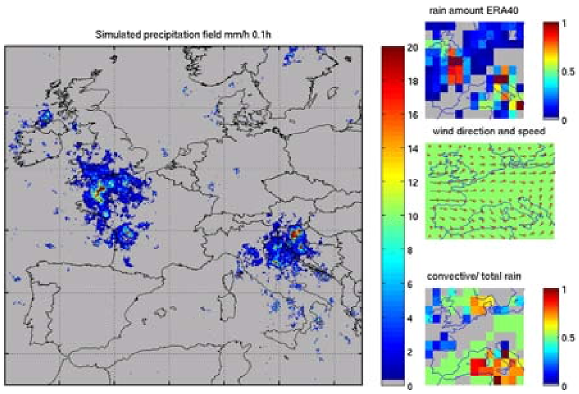

Figure 5. Typical simulated precipitation field

X. MAKING THE TERABIT/S SATELLITE A REALITY

As indicated above the straight application of current technology will not allow the proposed Terabit/s satellite to provide adequate QoS and thus we need to look towards innovations to solve this problem. Some possible areas are discussed below.

a) Improved C/I antenna performance

In order to achieve the capacity a large number of beams with a large overall frequency reuse factor is required. The downside of this is the increased interference components which sum up to contribute to the overall C/I. Current simulations of systems with a high number of spot beams demonstrate that the C/I is a significant challenge as the system is could be interference limited. Thus, in both the forward and return directions the satellite antenna C/I performance is an important factor in minimizing the number of beams required.

Some consideration has been given to the use of beam hopping on the forward link that may help to achieve flexibility with an acceptable number of RF chains and also to provide dual polarization in very hot spots with acceptable payload complexity but may not provide any improved C/I performance. For the reverse direction with many more beams and UT's the adoption of beam hopping is is much more difficult as in each beam the UT's would have to synchronized to the on board hopping which would complicate the terminals. However the return link is composed of bursts and there will be an activity factor associated with the transmissions across the beams and thus the aggregated interference considered so far is not a true reflection of reality. A more detailed investigation of the interference performance in general is thus needed.

b) Power requirements on the satellite

As already indicated payload power is likely to be a major constraint in achieving the Terabit/s. The HPAs already consume most of the payload power budget considered feasible (20 kW) and any special routing features (such as may be appropriate to match the Smart Gateway concept) will increase these demands.

c) Operation of ACM at Ka band and above

Conventional modulation and coding advances in the air interface have taken us close to the Shannon bound and therefore straight advances in this area will produce diminishing returns. Other means of increasing diversity that are applied in terrestrial systems suffer from the constraints of the satellite link apart from adaptive coding and modulation (ACM). ACM is being used effectively in DVB-S2 and partially in DVB-RCS at Ku band to combat rain fades by selecting one of twenty eight MOD/COD pairs available within DVB-S2. Such systems are constrained by the return link delay between the Gateway Earth Station and the UT compared with the time variation of the channel itself. As rain fading is a relatively slow mechanism it is possible to compensate fades across the MOD/COD range of 18dB, although in practice it will be slightly less than this. It is believed that at Ka band the current ACM could cope with the fading range for 99.7% availability on the UT links (but not higher) but for the Gateway Earth Station and Q/V bands the fades may exceed the current range. We have assumed that fades would not occur on both links simultaneously.

If we were to operate the UT's on Q/V bands we would need to examine a wider fading range and to extend the MOD/COD combinations. At the bottom end the system works down to an Es/No =-2.4dB and extending further is possible but will incur difficulties SNR estimation and synchronization. At the top end the issue is more power from the satellite but this could be preferable as schemes higher than 32 APSK, such as 64 APSK or 64 QAM, should be possible by 2020. However, the co-channel C/I may constrain any benefits from such an approach.

d) Achieving the availability on the Gateways

As indicated above in the system dimensioning rain on the Gateway Earth Station uplinks is a major problem at Q/V bands. We could employ up path power control but the range of fading is so large that this would bring with it other major problems. Site diversity could be used but finding an uncorrelated rain site with acceptable ground connections is expensive and may be impossible. Thus, as indicated earlier, we consider smart site diversity systems in which the Gateway Earth Station's are interconnected to a Network Control Centre (NCC) which connects UT beams to one of the Gateway Earth Station's from the pool. Thus when a Gateway Earth Station is indicated to go into a deep fade the NCC performs a handover to another unfaded Gateway

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Earth Station and switches all the UT forward and return links to that Gateway Earth Station. Since the Gateway Earth Station's are widely spaced a much better decorrelation of fading is available than for short distance diversity and the availability is increased. Including even a small number of Gateway Earth Stations in this configuration provides much improved availabilities at reduced fade margins. The handover process is crucial if no traffic is to be lost and at the same time we minimize signaling load in the system. Having established such a system it is also possible to include load balancing between the Gateway Earth Station's so as to ensure that outage switching doesn't cause an unexpected overload and to more balance the overall system.

As a more distant and challenging gateway architecture some studies are being initiated into the possibility of employing a network of gateways employing optical communications to the satellite. These studies will consider the maturity of the technology and the number of such gateways in the network.

XI. CONCLUSIONS

This paper has addressed concepts and issues relating to a Terabit/s satellite for 2020 that will be capable of reducing the cost/bit for broadband delivery and thus allowing satellite services to reach rural areas not feasible for terrestrial systems. The dimensioning of the system has demonstrated that several new technologies are appropriate for development before such a satellite system is feasible. Key amongst these are improved C/I techniques for the satellite antennas, smart Gateway Earth Station networks and improved ACM. Work is continuing to investigate all these in more detail but we feel there to be no technology show stopper for a Terabit/s satellite by 2020.

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