Evolution of Communications Payload Technologies for Satellites

ABSTRACT

Space is the military's loftiest "high ground". Historically, whoever held high ground had a significant advantage over its adversaries. This age-old principle is still true in today's wireless communications planning and siting of a base station or relay point, where a high point will ensure the best coverage and clear line of sight conditions to the end communicator. However, with the wide availability and use of satellites in all sectors of society, there is now a growing trend for satellite communications to be more than just relay or "bent-pipe". With some intelligent design and processing capabilities incorporated on board, satellites are able to meet the growing complexities of info-communications.

Liew Hui Ming
Koh Wee Sain
Lee Yuen Sin
Ter Yin Wei

Evolution of Communications Payload Technologies for Satellites

INTRODUCTION

Satellites have traditionally been bent-pipe devices for relaying information over large geographical areas in a single transmission, under the same coverage beam. The bent-pipe payloads used in most of today's networks perform purely frequency translation and signal amplification functions before the re-transmission of data to the ground.

To date, this is also the simplest payload architecture that a satellite can adopt. Technically, the primary advantage is its flexibility to accommodate different multiple access schemes, protocols and waveforms due to "transparency" or "waveform-free design" of its repeaters. However, the significant disadvantage is that it is highly inefficient in bandwidth utilisation, in that its "full-pipe" throughput results in the wastage of any unused transponder bandwidth, hence payload efficiency is reduced as this excess capacity cannot be reassigned to another satellite user. Another limitation of the bent-pipe payload is its relatively poor Bit Error Rate performance. Despite all these shortcomings, most commercial satellites are bent-pipes for economic reasons.

Push factors such as higher capacities of new generation applications and limited frequency spectrum resources are changing the way satellite systems are designed, implemented and operated. This article will focus on the key technology advancements in Satellite Communications (SATCOM) payloads used for telecommunications services.

To set the context of the various types of satellite payloads that were designed, a brief description on the different types of orbits for satellites and an outline on the international regulations governing the frequency coordination of the diverse satellite networks are provided.

TYPES OF ORBITS FOR COMMUNICATIONS SATELLITES

The first geostationary communications satellite, Syncom 3, was launched on 19 August 1964 from Cape Canaveral Air Force Base, United States (Sherman, 1997). It was placed in orbit at 180 degrees East longitude, over the International Date Line and was used that same year to transmit television coverage of the 1964 Summer Olympics in Tokyo to the United States. It was the first television programme to be sent across the Pacific Ocean.

Depending on the services offered and markets targeted, there are generally three broad

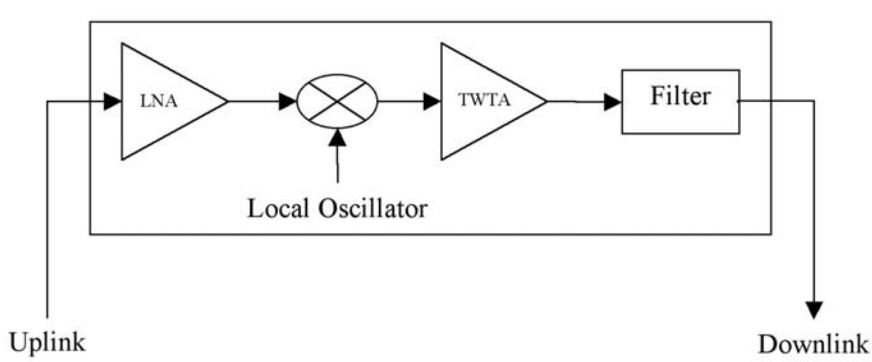

Figure 1: Schematic of bent-pipe payload (Gupta, 2003)

categories of orbits in which a satellite can take (depicted in Figure 2).

Geostationary Earth Orbit

A satellite in a Geostationary Earth Orbit (GEO) rotates in the same direction and at the same rate at which the earth spins. It orbits at an altitude of 36,000km above the Earth and according to Kepler's Third Law of Planetary Motion[1], a GEO satellite appears as a fixed point in the sky from the Earth's surface. This orbital location is also called the Clarke Belt, after the late British scientist and science fiction author, Arthur C. Clarke, who first suggested the theory of locating three GEO satellites in the Earth's equatorial plane to enable inter-continental communications in 1946 (Clarke, 1945). The advantages of such an orbit are that no tracking is required from the ground station (since the satellite appears fixed) and continuous operation can be provided in the "permanent" area of visibility of the satellite. Many communications satellites (e.g. INTELSAT, INMARSAT, and SingTel's ST-1) are placed in such an orbit.

Low Earth Orbit

A Low Earth Orbit (LEO) system typically circles at an altitude of 500km to 2,000km above the Earth and makes one revolution in about 90 minutes. LEO satellites, usually arranged in constellations of more than about 18 satellites (e.g. ORBCOMM[2], LEO ONE[3]), are needed to provide uninterrupted connectivity over a certain coverage area. They are able to offer reduced signal loss and less latency in the transmission to the ground terminals since these satellites are 20 to 40 times closer to the Earth than GEO satellites. This means that satellite antennas can have proportionately smaller aperture sizes, thus allowing for smaller user terminals. Other well-known LEO communications satellite constellations include IRIDIUM and GLOBALSTAR. Discontinuous coverage is also achievable using a LEO satellite to relay a message transmitted from the ground by storing it first until the satellite comes in range of a receiving station and relays that

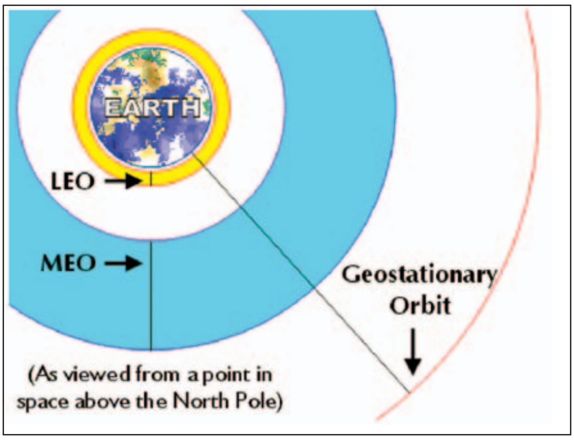

Figure 2: Different types of satellite orbits (ITS, 2002)

message. This mode of operation is usually applicable for applications that do not require real-time information feed (e.g. CASCADE[4] payload of Canada's CASSIOPE).

Medium Earth Orbit

A Medium Earth Orbit (MEO) system operates at an altitude of 8,000km to 20,000km above the Earth and requires a constellation of 10 to 18 satellites (less satellites as compared to a LEO system due to the higher altitude of MEO systems) in order to achieve constant global coverage of the Earth. It introduces less latency and delay in information transmission than a GEO satellite (but greater latency and delay than that of a LEO satellite) and enables antennas of modest size for ground users. The orbital periods can range from about two to 12 hours. An example of a MEO system is the ICO Global Communications.

INTERNATIONAL TELECOMMUNICATIONS UNION REGULATIONS ON SATELLITE NETWORKS

At present, there are at least 300 GEO satellites[5] in operation within 360 degrees of the whole orbital arc. That works out to be one satellite occupying at almost every one degree of spacing[6] based on pure statistics calculation. Protection against interference between the systems is therefore necessary and this can be alleviated via proper planning of the orbital positions and frequency bands for enhanced utilisation of this limited natural resource.

International Telecommunications Union Coordination Process

International Telecommunications Union (ITU) establishes the satellite coordination procedures for both GEO and non-GEO satellite networks and plays a pivotal role in regulating the use of orbital slots in space for operating satellite systems as well as coordinating the use of frequency resources (Henri, 2006 and Federal Communications Commission, 1999). The procedures are built upon the main principles of ensuring efficient use of the orbit and equitable access to spectrum resources. The ITU coordination process essentially comprises three steps[7].

- Advance Publication (Section I, Article 9)
- Request for Coordination (Section II, Article 9)
- Notification / Recording of Satellite Systems (Article 11)

It is also important to note that the ITU radio regulations are not intended to provide information on how satellites should be designed. Rather they create the opportunity for the industry to construct and operate a cost-effective yet multi-functional spacecraft to meet the communications services needed by the market.

In addition, it is mandatory for all spacecraft, regardless of GEO or non-GEO, to be fitted with devices which ensure immediate cessation of radio emissions whenever such cessation is required (Section 1, Article 22).

International Telecommunications Union Frequency Allocation and Associated Communications Services

For the purpose of managing the global radio spectrum, ITU divides the world into three regions to facilitate the allocation of radio frequencies:

- Region 1: Largely Europe, Russia, Africa and parts of the Middle East
- Region 2: Mainly the continents of North and South America
- Region 3: Mostly Asia

Figure 3: ITU region map (Nomura, 2006)

With the region map in place, ITU further defines the frequency allocation and the associated categories of services for the respective regions. Table 1 provides a summary of the communications satellite services, permissible for use in Region 3 as an example.

Table 2 lists the major categories of satellite services, as defined by ITU.

NEXT GENERATION COMMUNICATIONS SATELLITES

With the commercialisation of satellite services, especially Direct-To-Home and the arrival of Internet Protocol Television (IPTV), coupled

Frequency Band	Frequency Range based on ITU definition (GHz)	Types of Communications Services for Region 3
L	1-2	Broadcasting Satellite Service Mobile Satellite Service
S	2-3	Broadcasting Satellite Service Fixed Satellite Service Mobile Satellite Service
C	4-8	Fixed Satellite Service
Ku	12-18	Broadcasting Satellite Service Fixed Satellite Service Mobile Satellite Service
Ka	27-40	Fixed Satellite Service Mobile Satellite Service

Table 1: ITU frequency allocation table (Federal Communications Commission, 2007)

Types of Communications Services	Acronym	Description
Broadcasting Satellite Service	BSS	Sometimes known as Direct Broadcasting Service (DBS), it provides television and radio broadcast via the satellite such as Direct-To-Home services (e.g. INSAT) and satellite radio.
Fixed Satellite Service	FSS	Refers to a satellite service which uses fixed terrestrial terminals for applications like telephony, broadband Internet access and Very Small Aperture Terminal for communication.
Mobile Satellite Service	MSS	A satellite system that enables the use of portable terrestrial terminals e.g. satellite telephones that allow global phone service anywhere, anytime (e.g. INMARSAT, IRIDIUM).

Table 2: Major categories of satellite services defined by ITU

with the liberalisation of the SATCOM industry, a huge demand for high-speed, broadband capacity was created as the trend moved towards bandwidth-hungry applications for Fixed Satellite Service (FSS), Broadcasting Satellite Service (BSS) and Mobile Satellite Service (MSS)[8].

Communications satellite systems have been developed to respond to such demands. These adaptations include the following:

- Use of higher frequency bands
- Addition of more transponders on the satellite and
- Closer orbital spacing (now at two-degree separation for FSS).

However, these measures fall short of bringing satellite systems to the next level. Next generation satellites will need to have design enhancements to the SATCOM payload, mainly in on board processors, Antenna and Radio Frequency subsystems, while employing advanced techniques in increasing both capacity and capability. These may constitute on board payload processing, advanced antenna designs and frequency re-use.

KEY TECHNOLOGY TRENDS IN COMMUNICATIONS PAYLOAD

The following sections describe the main enabling technologies and designs that are currently shaping the development landscape of the SATCOM payload in providing improved network flexibility, capacity and performance in new and upcoming satellites.

Channelisation Technology

A major highlight in the SATCOM research and development in recent years is the emergence of the channeliser, which is poised to solve the current limitations of bent-pipe SATCOM systems. In a conventional transparent satellite transponder, regardless of the amount of bandwidth one uses in the uplink beam, the entire beam will be transponded into the downlink beam. With an analog channeliser, it divides the uplink beams into multiple sub-channels and independently routes them to their respective downlink beams, thus improving bandwidth utilisation. This analog channeliser technology has been implemented in a few commercial satellites, such as ANIK-F2 and AMC 15/16.

The digital channeliser brings this capability further by enabling circuit switching between different beams of transponder bandwidth at much smaller sub-channels. These techniques promise to increase capacity usage on multi-beam satellites by providing routable bandwidth on demand. The Wideband Global SATCOM (WGS), a military SATCOM or MILSATCOM constellation, is believed to be the first to implement the digital channeliser (Elfers, 2002).

There are shortcomings in using analog devices for satellite routing and channelisation since they are usually heavy and have large power consumption. As it is critical in the design of a satellite to achieve lighter weights and larger system capacity, advancements in Very-Large-Scale Integration (VLSI) technology has allowed the replacement of some analog components with digital components. This progression will lead to a satellite of smaller mass with lower power consumption but will result in a much higher overall system cost due to expensive digital components. However, channelisation technology is still expected in newer satellites yet to be launched though it is likely to be based on a combination of both analog and digital components considering the mentioned trade-offs.

All in all, this technological breakthrough is significant for both commercial and military applications. The increased capacity usage for the same payload translates to higher revenue potential and a greater return on investment. For military applications, it can serve as a counter-measure to mitigate unintentional interference and jamming.

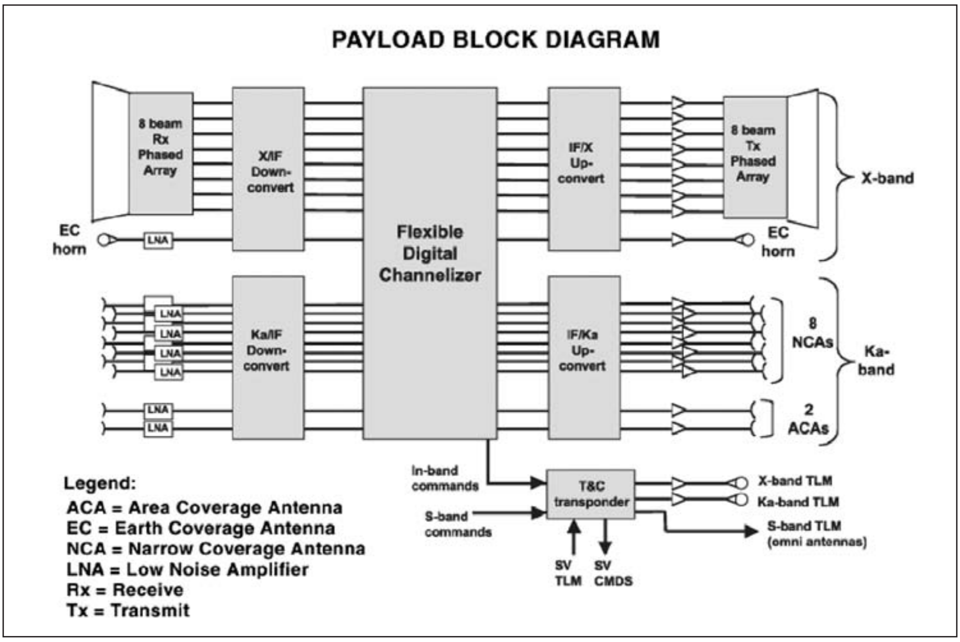

Figure 4: Payload design of WGS (BOEING, 2007)

Space-Based Inflatable Reflector Antenna

Satellite antennas have evolved since the last two decades from small-sized solid reflectors (2m to 3m in diameter) to large, lightweight deployable antennas (5m to 30m in diameter) for providing high aperture power to the desired ground coverage. Previously limited by launch vehicle fairing and packaging constraints, deployable antenna technology has been demonstrated in the 12.25m parabolic reflector of the Thuraya (L-band) satellite and more recently, the 9m (L-band) reflector of the INMARSAT 4 satellite.

Figure 5 shows an Astro Mesh reflector supplied by Northrop Grumman Astro Aerospace of Carpinteria, California fully deployed on the INMARSAT 4 Satellite. Astro Aerospace received an award from the Royal Aeronautical Society for designing a smaller packaged and lighter deployable reflector (Northrop Grumman, 2007).

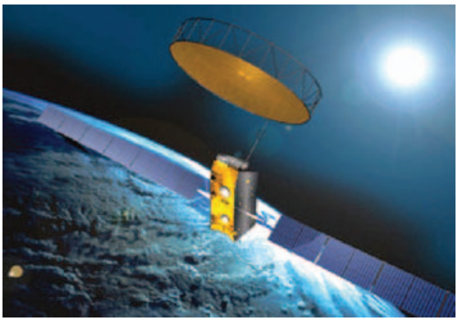

Figure 5: Mesh reflector on INMARSAT 4 satellite

Multi-Beam Antenna and Steerable Beam Antenna

The advent of Multi-Beam Antenna (MBA) and Steerable Beam Antenna (SBA), especially those that utilise transponders in and above the K-band frequencies, is gaining importance in commercial SATCOM systems. These antennas offer a high degree of network coverage adaptability and, in order to meet the dynamic market demands, are able to create multiple

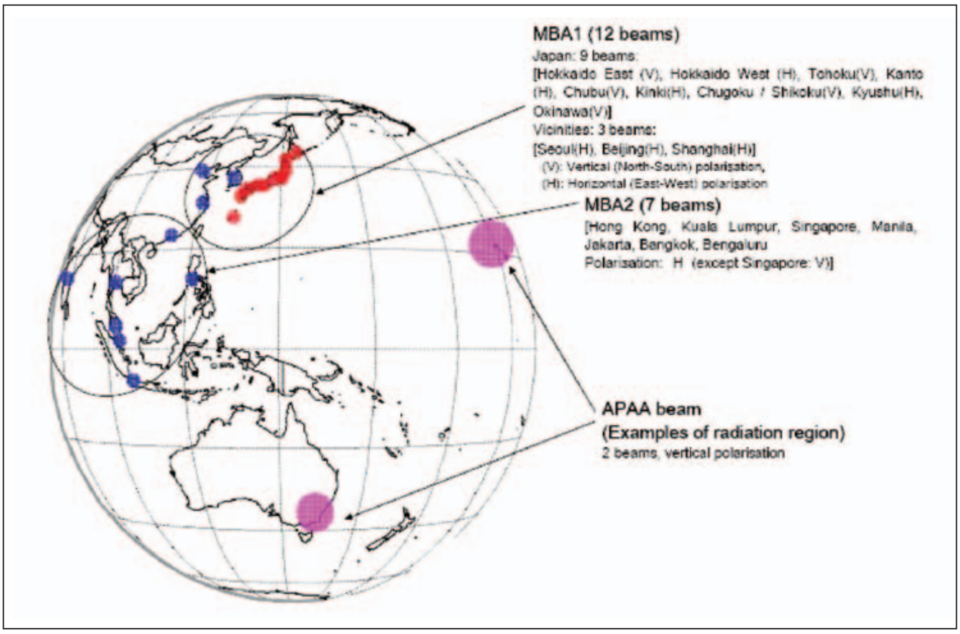

Figure 6: Planned MBA coverage under WINDS (Ministry of Public Management, Home Affairs, Posts and Telecommunications, 2003)

narrower beams, particularly in the overly congested C-band spectrum that is also being accessed by terrestrial wireless services. This technology is beginning to make commercial sense as using multiple spot beams over different geographical areas can increase bandwidth utilisation, therefore enhancing system capacity through frequency re-use. Furthermore, the use of spot beams instead of global beams improves the SATCOM link performance. As a result, receive-only ground antennas can be substantially smaller.

Another vital advantage of the use of such multi-beams and steerable antennas is their effectiveness in combatting the rain fade issues for frequencies in and above the K-band. This is especially notable in the rain-prone tropical region whereby C-band spectrum availability is of imminent concern and higher frequencies like Ku, Ka, V and even Q-bands are viable options for a variety of communications applications.

Examples of satellite systems that are equipped with these capabilities include:

- The Japan Aerospace Exploration Agency's (JAXA's) Wideband InterNetworking engineering test and Demonstration Satellite (WINDS)[9] programme employs MBAs with high power Multi-Port Amplifiers to provide flexible power assignments (Shimada, 2006). The satellite system is currently under development and has completed the acoustics and vibration tests (JAXA, 2007).

- SPACEWAY is a next generation commercial satellite system, operating in the Ka frequency band that employs multi-spot beams technology. The SPACEWAY 3 satellite was successfully launched in 2007 (Hughes, 2007).

- HOTBIRD 3 has a SBA, where its steerable beam can cover all points of the globe visible from 13°'a1 East in both the Northern and Southern hemispheres (Geo-Orbit).

- The Advanced Communications Technology Satellite (ACTS) (Kramer) employs both MBA and SBA technologies, and its spot beams hop sequentially within each other in a Time Division Multiple Access fashion.

Internet Routers in Space

The US Department of Defense (DoD) recently awarded INTELSAT a Joint Capability

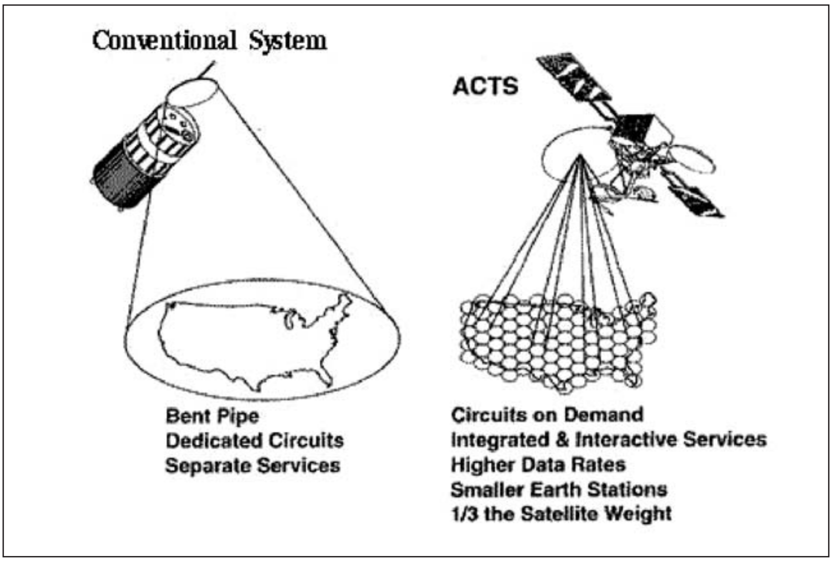

Figure 7: Multi-Beam antenna technology in the ACTS

Technology Demonstration (JCTD) Programme, titled "Internet Routing In Space (IRIS)". This three-year programme represents the first foray into putting an Internet Router as part of the satellite communications payload. Cisco will provide commercial Internet Protocol (IP) networking software for the on board router, while SEAKR Engineering Inc. will manufacture the space-hardened router and integrate it into the IRIS payload. The satellite, IS-14, is set for launch in the first quarter of 2009 and will be placed in geostationary orbit at 45 degrees West longitude with coverage of Europe, Africa and the Americas.

IRIS will serve as a computer processor in the sky, merging communication data received on various frequency bands and transmitting them to multiple users based on data instructions embedded in the uplink. Specifically, the payload will support network services for voice, video and data communications, enabling military units or allied forces to communicate with one another using IP and existing ground equipment.

The payload will interconnect one C-band and two Ku-band coverage areas. The IRIS architecture and design allow for flexible IP packet (layer 3) routing or multi-cast distribution that can be reconfigured on demand. With the on board processor routing the up and down communications links, the IRIS payload is expected to enhance satellite performance and reduce signal degradation from atmospheric conditions.

Communications Payload for Surrogate Satellite Platforms

There is a new league of "surrogate satellite" communications payload, designed for deployment on High Altitude Platforms (HAPs) or stratospheric platforms, which are capable of delivering similar broadcast, fixed and mobile communications services for regional area coverage. These platforms, either in the form of airships or planes, will be situated at about 20km above the Earth to capitalise on the undeveloped space between the terrestrial and space domains, akin to a rapidly deployable "GEO" at 20km altitude. The underlying component technologies are similar to the technology developed for both satellite and terrestrial radio systems. For instance, flight tests of Ku frequency band and millimetre-wave communications were conducted using a helicopter together with the development and use of multi-beam antenna i.e. MultiBeam Horn and Digital Beam Forming Antenna on board the platform (National Institute of Information and Communications Technology, 2002). Besides the US and Europe, Asian countries like Japan, Korea and China are actively involved in exploring HAPs as satellite gap fillers in the event of loss of space assets.

Other Technological Advancements

Though the development of power amplifiers as a driving force in satellite communications has been subtle, it is undeniably changing the face of satellite usage. Developments in helix Travelling Wave Tubes have made forays into new frontiers and made significant achievements in size reduction, conduction cooling and efficiency gains by using multi-stage collectors. With the onset of more powerful power amplifiers, ground antenna dish sizes promise to become smaller, leading to more prevalent usage of higher-frequency bands like Ku and Ka.

Interactive multimedia services via satellite look set to be the next big wave with the introduction of multiple spot beams and the consolidation of open standards based on the successful Digital Video Broadcast–Satellite (DVB-S) or Digital Video Broadcast-Return Channel over System (DBV-RCS). Coupled with on board processing techniques, the result is an interactive system that is compatible with the open standards of DVB-S (downlink) and DVB-RCS (uplink), multi-beaming over several coverage areas. AmerHis is an advanced communications system carried by Hispasat's Amazonas satellite. Its DVB on board processor has the capacity to provide the demodulation, decoding, switching, encoding and modulation for the four transponders on Amazonas. Each Ku-band transponder covers one of the four geographical regions served by the satellite, namely Europe, Brazil, and North and South America.

In recent years, open standards such as the Digital Video Broadcast-Satellite 2 (DVB-S2) have emerged. Some of its key features are the dynamic assignment of coding and modulation, and traffic conditioning which are key enablers for dynamic bandwidth allocation and optimisation. The new developments will help to break down the barriers caused by the current proprietary ownership of some of these techniques, and hence drive the cost of market equipment downwards. In MILSATCOM, plans are underway in the US DoD to implement these open-standards dynamic bandwidth resource allocation techniques, with additional features such as dynamic resource assignment across uplink and downlink beams, and even Multi-Level Precedence and Preemption in their Tactical Satellite programme.

CONCLUSION

Satellite systems have come a long way since their evolution in the 20th century, as seen in the wide array of applications such as telecommunications, TV broadcasting services, navigation and weather monitoring. Satellite systems are now an integral part of the global ecosystem and are set to continue to play a bigger role in our daily lives.

The conventional bent-pipe satellite architecture will form the foundation for continued augmentation in support of the expanded growth in SATCOM network services in the immediate and near term.

However, for the long term, the next generation satellites necessitate the employment of new technologies in communications payload, in view of the physical constraints and availability of frequency spectrum and orbital space congestion. "Super-computers-in-the-sky", with higher power amplifiers, larger and smarter antennas, are poised to create more capacity and space out of these constraints, to meet the future needs of a fully connected planet.

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ENDNOTES

1. Kepler's third law states that the squares of the orbital periods of planets are directly proportional to the cubes of the semi-major axes of their orbits. This expresses the distance to all the planets relative to earth's orbit by knowing their period.

2. The ORBCOMM has a constellation of 29 operational LEO communications satellites in six orbital planes that provide worldwide coverage.

3. The LEO ONE has a constellation of 48 LEO communications satellites arranged in eight orbital planes at an altitude of 950km.

4. CASCADE is a communications payload demonstrator scheduled to launch in 2007. It is positioned to be the first space-based digital courier service based on store and forward file transfer techniques, operating in the Ka frequency band. CASCADE is designed to deliver data files of between 50 to 500Gbytes at transmission speeds of 1.2Gbyte/s when a ground station is within view of the spacecraft. This service is expected to be available commercially by 2009.

5. Information extracted from http://www.lyngsat.com on 24 August 2007.

6. The two-degree orbital spacing policy by ITU ensures Fixed Satellite Service (FSS) satellites in geostationary orbit can operate without causing interference to neighbouring GEO FSS satellites located as close as two degrees away.

7. Note that only non-GEO satellite networks in certain frequency bands governed by the

No. 9.11A procedure are subjected to advance publication and coordination procedures. Other non-GEO satellite networks (all pertinent services and certain frequency bands) will require only the advance publication procedure before notification.

8. These are major categories of satellite services as defined by ITU. Besides FSS, BSS and MSS, there are also Earth Exploration Satellite Service and Radiodetermination Satellite Service. One satellite can be made up of a number of satellite networks providing a combination of services, such as FSS, BSS, or MSS, in a number of different frequency ranges.

9. JAXA has become one of the world leaders in communications, positioning experiments and engineering research in the area of satellite applications. Its WINDS programme, which promises a maximum speed of 155Mbps for households and 1.2Gbps communications for offices, has been launched in 2007 (Shimada, 2006). On top of delivering large-capacity international Internet access, it aims to enable advances in telemedicine to remote areas.

BIOGRAPHY

Liew Hui Ming is Principal Engineer and Programme Manager (Information). As Programme Manager, Hui Ming develops and charts out the Long-Term Defence Technology Plan for IKC2 Advanced Communications as part of the R&D portfolio. He also develops and implements the Singapore Armed Forces (SAF) Satellite Communications Programme, as part of the five-year plan to operationalise the Third Generation SAF ONE Network. Previously, as a Systems Architect specialising in Satellite Communications, Hui Ming took on the lead role in establishing the systems architecture and strategy on how the customers are to embrace the use of Satellite Communications technologies and solutions for their business operations and requirements. He graduated with a Bachelor of Engineering in Information Systems Engineering from Imperial College, London in 1996 and a Master of Science in Electrical Engineering from the National University of Singapore in 2001. He also won the DSTA Team Excellent Award in 2003 and 2006.

Koh Wee Sain is Senior Engineer and Project Manager (Communications and Tactical C2). As Project Manager, Wee Sain develops and implements the SAF Satellite Communications System to operationalise the Third Generation SAF ONE Network. He is also responsible for assessing emerging beyond line of sight wireless technologies for the SAF. Previously, Wee Sain was involved in the setting up of the SAF Centre for Military Experimentation. He graduated with a Bachelor of Electrical and Electronics Engineering from Nanyang Technological University (NTU) in 1999. He won the DSTA CSO Innovation Excellence Award (Individual) in 2001 and the DSTA Team Excellent Awards in 2004 and 2005.

Lee Yuen Sin is Senior Engineer and Project Lead (Communications and Tactical C2). As Project Lead, Yuen Sin is responsible for the implementation of SAF Satellite Communications Programme for the Third Generation SAF. She is also involved in the assessment of emerging non-terrestrial wireless communications technologies and systems. Previously, as a senior consultant in SCME, she was the key player in designing, conducting and analysing C4I experiments that explore future operational concepts enabled by cutting-edge technology. She graduated with a Bachelor of Electrical and Electronic Engineering from NTU in 2000. Yuen Sin won the DSTA Team Excellent Awards in 2003 and 2006.

Ter Yin Wei is Senior Engineer and Project Lead (Communications and Tactical C2). As Project Lead, Yin Wei is involved in the execution of the SAF Satellite Communications Programme, and conducts critical technical analyses on matters relating to the programme, as part of the overall plan to realise the Third Generation SAF ONE network. Previously, Yin Wei was involved in the implementation of satellite communications network management systems for Joint and Army. She was also a member of the team that drove the implementation of the next-generation satellite communications technologies for the SAF, including the charting of satellite communications network architecture. She graduated with a Bachelor of Applied Science in Electrical Engineering from the University of Toronto under the Defence Technology Training Award.