Australia in Space: a strategic plan for Australian space science

Working Group Report

Working Group Topic: Communication Technologies

Chair: Adj Prof W.G. Cowley, Univ of South Australia
Members: Drs. G. Bolding and B. Clare, DSTG; Dr F. Bennet, ANU, Prof C Fumeaux, Univ of Adelaide; Adj Prof N Weste, Macquarie Univ; Prof G. Lechner; Univ of South Australia
Disclosures of interest: Prof Weste: VP Engineering, Morse Micro Pty Ltd, NSW; Prof Lechner: Communications Program Director, SmartSAT CRC;

Vision statement

The year is 2030 and the rapid growth in telecommunications has continued, both in space and on the Earth. The number of Internet-of-Things (IoT) devices on Earth has passed hundreds of billions, with a significant fraction connected from space. Mega constellations of small Low Earth Orbit (LEO) satellites have become commonplace, supplying broadband services in areas with poor terrestrial coverage. Optical communication links have been deployed for many backbone global networks. SATCOM is increasingly used for emergency service restoration after climate-related disasters. From the perspective of end-users, terrestrial networks and satellite networks have merged completely with no noticeable handover effects between them. Communications latency is at a minimum as most traffic worldwide is routed over redundant LEO satellite links. Many optical links already utilize quantum key distribution (QKD) to generate common keys, which can then be used for encryption. Further microelectronics progress in system-on-chip technology has allowed more robust and adaptive networks, able to exploit higher frequency bands.

The proliferation of satellites has resulted in an increasingly congested Radio Frequency (RF) environment. Space is more accessible but possibly less regulated, exacerbating the RF interference issues associated with the congestion. Government, Military and Commercial agencies increasingly deal with interference that impacts the reliability of services. With the complexity of multiple orbits, diverse satellite technologies, co-operative and non-cooperative legal jurisdictions and ‘non-regulated’ users, the search for resilience and quality of service has turned toward exploiting diverse resources. Ground and airborne terminals are often equipped with hybrid RF/optical systems, generally with at least two RF bands available. The use of higher frequency bands (70-90GHz) for SATCOM has been enabled by technology developments. Cognitive radio concepts have been extrapolated to ‘cognitive space’ where terminals and satellites work autonomously to maximise communications availability across the resources they can access, both private and public.

Background

Satellite communications have traditionally been provided using RF spectrum. Unfortunately this limited resource has become very congested. Spectrum allocation is a lengthy and expensive progress, requiring extensive international coordination. Efficient use of spectrum has been difficult due to the constraints of space-segment electronics, inflexible licensing and the need to avoid interference.

Recognition of the change in paradigm from a ‘noise limited’ SATCOM channel to one that is interference limited is emerging in literature [1]. This paper focuses on single High

Throughput Satellites (HTS) and Very HTS, but is an indicator of the future where the issue could further extend across multiple satellites, increasingly relevant due to the small size of antennas on ‘User Terminals’ causing interference into other satellite systems. The key to operating in such an environment will be advanced signal processing (interference mitigation techniques) where channel estimation, beamforming and multiple input, multiple output (MIMO) techniques, plus commensurate waveform standards (such as DVB-S2X) combine to provide a way forward. Whilst the scenario is highly complex and exacerbated by signal propagation delays associated with geostationary satellites, it is likely tractable with ongoing technology development. Techniques to efficiently deal with the processing complexity, and indeed to extend the scenario to resource ‘sharing’ across multiple satellite systems combined with terrestrial spectrum co-use, are of interest in making the best use of limited spectrum resources in a bandwidth hungry world. Australia, originally through the University sector and more recently via a small number of startup companies, has a rich history and extant capability in signal processing as applied to SATCOM, and is in a position to contribute to and capitalise on developments in this area.

Satellite on-board electronics are becoming more capable through increased flexibility (reconfigurable or reprogrammable electronics) plus the ability to operate in higher frequency bands. These advances allow higher-throughput communication payloads to operate in small satellites. Advances in microelectronics clearly underpin much of the progress in telecommunications. Through 20 years of WiFi CMOS System on Chip design, Australia has key expertise in this area. System on Chip (SOC) refers to the ability of a (largely) digital technology to include key analog and RF systems on a single monolithic technology (i.e. single chip). This leads to power, size and cost points that cannot be approached by any other technology. This is difficult technology to design and fabricate with acceptable performance and yield, yet crucial for future progress. Similar expertise is required for the Reduced Instruction Set Computers (RISC) that control satellite payloads and provide DSP capability. CMOS System on Chip technology, combined with Gallium Nitride (GaN) DC and RF power technologies, will dominate space borne electronics for the foreseeable future. A case study on GaN is included below (case study 1).

One estimate [2] indicates there are 2,062 active artificial satellites orbiting the Earth (March 2019). The UCS Satellite Database [3] identifies 846 of these as directly (and actively) providing communications (and this excludes a large number, 283, principally Low Earth Orbit, associated with ‘technology development/demonstration’, which would include a proportion of communications functions, conservatively 25%). In 2015, similar data estimates 2000 of the 4077 satellites in orbit (not all active) were communications satellites. This data indicates that ~45-50% of all satellites are communications satellites! From 2020 we anticipate the emergence of satellite networks comprising very large numbers of small satellites, for example, Starlink [4] from SpaceX is reportedly based on ~12,000 satellites. Traditional communications satellites in geostationary orbits will remain important, but their relatively large communications latency renders them sub-optimal for voice and IoT communications. Enabled by optical satellite-to-satellite links, mega-constellations of satellites in LEO orbits will carry large amounts of data with latencies even lower than terrestrial options. The LEO constellations have the ability to serve almost all of the globe, providing high-speed connectivity for remote areas - this will have a massive impact on traditional telecommunications operators. These new constellations will also prove valuable when terrestrial infrastructure is unavailable - such as in conflict regions and after natural disasters. Some of the LEO constellations will be augmented by geostationary high-altitude platforms (HAP).

Traditionally communication payloads have used simple wire or patch antennas on small satellites or deployable parabolic antennas on large communication satellites in GEO orbit. The advances in CAD techniques and computing hardware have revolutionised antenna engineering capabilities. Devices with increasing complexity and enhanced performance (gain, efficiency, and bandwidth) can be digitally modelled and optimised with a high level of fidelity in geometry and materials. The radiation characteristics of multiple antennas or arrays mounted on platforms, from cubesats to large satellites, can be accurately predicted, even in the higher frequency bands. Additional mechanical requirements such as stowage mass and volume, deployment methods and pointing capability are key characteristics that can be co-designed in dedicated CAD tools. Australia has some excellent antenna expertise, mainly located in the CSIRO, specialised enterprises and selected universities. Focussed activities include satellite-on-the-move, ground station and cubesat antennas, as well as fundamental research from low frequency bands to the terahertz regime. An example case study is presented below (case study 4).

Optical fiber carries the bulk of terrestrial communications but until recently the use of free-space optical (FSO) has been limited by atmospheric effects and size/mass constraints in space. The former can be addressed by error correction, adaptive optics and diversity techniques. Given the pressure on the RF spectrum, laser optical communications between satellites and from space to ground has become common for Earth Observation (EO) telemetry data, with larger satellites. New opportunities are available given rapid progress in the last several years with miniaturised pointing assemblies and inertial reference stabilisers, providing opportunities for a great expansion in FSO SATCOM. Australia has developed significant expertise and international collaborations in FSO communications during the last decade and stands to benefit from these developments given suitable support. Case study three describes a DST small satellite mission hosting an experimental FSO communications payload.

Besides benefits of smaller, lower-power FSO terminals, the lower beam divergence gives more secure communication at the physical layer plus the ability to carry quantum information for “un-hackable” security. Quantum communication techniques can be used to transmit encrypted information or encryption keys in a way which prevents anyone from decrypting or hacking the transmission. The laws of physics themselves are used to secure the communication channel to provide the only provably secure communication method. One future application of this will be to establish a global quantum network. Quantum communication satellites will be able to distribute information around the world and exchange encryption keys in an ultra-secure manner. This would enable the connection of continents with secure networks. Australia has excellent expertise in this area. An example case study is presented below (case study 2).

Issues Table

Insight	Aspiration	Actions	Impacts	Metrics
Communication resources in space are becoming more prolific. This increases potential capacity but RF interference has a limiting effect. Signal processing techniques, free space optical communications and the use of higher frequency RF bands provide a way forward	Maximise the use of resources for resilient, reliable, available communications despite the congested environment	Develop terminals with RF band/hybrid optical/RF diversity, capable of operating with more autonomy, independently or cooperatively, integrated with a broader more complex and aware Satellite resource control environment. Promote awareness of the standing capability in SATCOM signal processing in Australian Universities and the opportunity this represents for future STEM professionals for ongoing contributions.	Investment in communications capacity in space can continue without the self-limiting effects of interference. Reliability and availability are maintained. Delivery of increased bandwidth from space is achieved with the broader societal economic, safety and security benefits	Societal benefit. Communications Availability, Reliability and Bandwidth. Spectral efficiency (bit/sec/Hz) achieved relative to investment in capacity on orbit.
Lack of students in specialized topics such as high end integrated circuit design, or advanced antenna modelling	More students, especially women	Marketing to alert young people to opportunities. Professional scientists and engineers provide example problems and projects to motivate student 'missions'. Make this available at a web portal for teachers and students.	Critical Mass of knowledgeable students	Number of PhDs relevant to advanced SATCOM
Lack of networking of people with key technology knowledge	Knit people together - "Team Australia"	Convene technology workshops and forums to educate people what expertise is available	Enable people to propose and carry out keynote projects (e.g. complex SOC payload designs)	Number of SATCOM payloads and ground stations.
Australia can offer site diversity for an FSO ground station network.	Ground station networks for improved remote area and regional communications	Development of rugged optical GS equipment, plus telescope technology, integrated GS networks and protocols.	Better connectivity of remote and regional areas via high rate FSO downlinks; more EO data with lower latency	Size of GS network; availability, throughput.

Eavesdropping and decryption of intercepted communications signals	Quantum encryption technology for global communication security	Trials of quantum technology such as QKD and quantum memory, ruggedisation of quantum components, demonstration of satellite quantum sources and receivers	Ultimate security for global communications with a global quantum network (e.g. memory in space)	Provable security between terminals e.g. between continents

Recommendations:

The Academy of Science should promote both national and international collaboration between Australian organisations with interests in next-generation satellite communication techniques by:

- wherever possible, promoting the actions included in the Issues Table of this report
- approaching the SmartSat CRC Board and suggesting they devote one session of their regular CRC conference to an externally-promoted open-invitation show-and-tell session related to advanced SATCOM technologies. The ASA and the Australian Space Forum could also be consulted. Given the multidisciplinary nature of future satellite communications, this session would aim to inform and link local organisations with relevant specialist expertise.
- promulgating the supplementary information attached to this report, for example on its own web pages and by encouraging the Australian Space Agency to establish a web portal for information relating to local R&D directed at, or applicable to, new SATCOM techniques.

Case Study #1 **High Frequency MicroElectronics: Capability and Training**

Gallium Nitride (GaN) is a high speed technology for very high frequency amplifiers and power conversion circuits. Australia has built some small beachheads in GaN design at the University of Adelaide under the leadership of Dr Aaron Periera and Altum RF in Sydney under Tony Fattorini. GaN fabrication is currently carried out in Taiwan, China, the US and Europe. GaN circuits (and their design) are a key platform for satellite systems both for radio systems and efficient power conversion. For example, DSN network transmitters are moving to GaN based power amps and NASA is currently investigating GaN-based orbital SARs. Figure 1 shows a recent example from a collaboration between Adelaide University and the Fraunhofer Institute [5].

It would be desirable to consolidate our leading position under Dr Pereira by providing funds for prototype GaN chip fabrication and the training of new graduate students. Altum RF can be supported by perhaps support for development contracts for mm-wave satellite systems. This capability could also possibly be used by defence companies such as CEA in Canberra.

Millimetre wave (mm-wave) circuits are a key platform for satellite systems of the future. Currently Australia has a small but capable mm-wave circuit design capability. Two companies of note are Altum RF who specialise in the design of GaAs and GaN circuits and Movandi who design CMOS mm-wave circuits under the leadership of Dr. Michael Boers (their HQ is in the US). There is also mm-wave CMOS design experience in Melbourne (originally under Dr. Stan Skafidas - Nitero that was acquired by AMD).

Given the complexity of advanced microelectronics design and its underlying importance in future spaceborne communications, we recommend nurturing existing courses in this area and support for new programs. (See Issues Table).

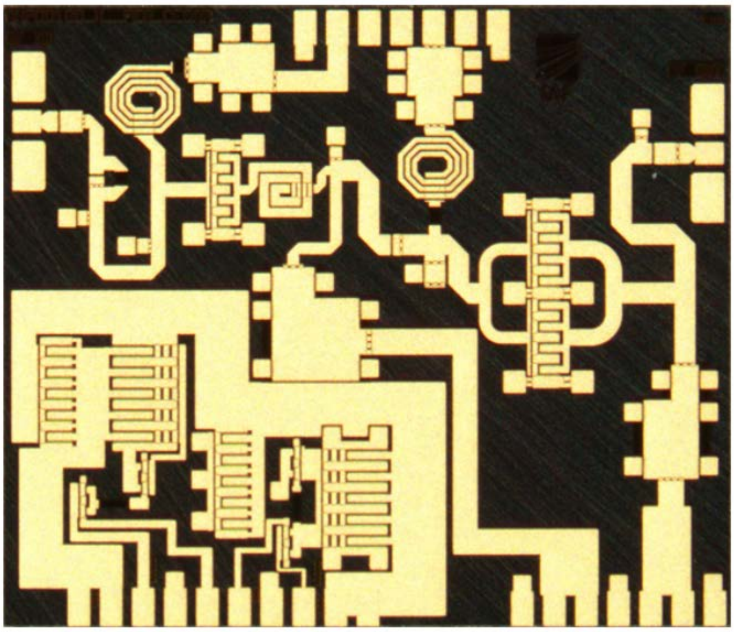

Figure 1. Photograph of IC that integrates for the first time a modulator and 3W power amplifier for X Band aerospace applications, fabricated in 0.25*u*m GaN.

Case Study #2 **Australian Collaboration with DLR in optical communications**

Australia has excellent expertise in satellite communications and photonics. While this hasn't been combined at large scale for optical satellite communications yet, there are a number of recent activities in this area, which are supported by international partnerships. The German Aerospace Center (DLR) has a well-established track record in this area with strong international collaborations. For more than 10 years the University of South Australia has collaborated with DLR in the area of high speed channel coding for optical channels affected by atmospheric scintillation. This work included staff exchanges, field trials and the development of hardware testbeds.

More recently, QUOLLSat, a quantum communications satellite mission by ANU and the German Aerospace Center DLR, is a potential civil space flagship mission for Australia using technology developed at ANU to demonstrate world-leading quantum communication capabilities. The satellite's advanced optical communications payload and telescope will generate and transmit quantum information from space, offering highly-secure communication. This mission will use ANU's innovations to change the way quantum communication networks can be used in space. Australia's point of difference is the ANU-developed 'quantum memory' and continuous-variable quantum source. These components enable quantum information to be transmitted, stored and routed across a global network.

Case Study #3 **Buccaneer CubeSat Programme**

Australia's Defence Science and Technology Group plans to launch the Buccaneer Main Mission CubeSat in early 2022, with the primary mission to explore how a space-based High Frequency (HF) receiver can calibrate and optimise the performance of the Jindalee Operational Radar Network (JORN). This launch will follow from the successful launch and operation of the exploratory Buccaneer Risk Mitigation Mission in 2017 (see Figure 2). Buccaneer will also carry additional payloads. One of these is a laser terminal, provided by Aerospace Corp., which aims to demonstrate high speed space-to-ground optical communication. The Buccaneer programme will advance Australia's expertise in space experimentation and research and provide a stepping stone to significant sensing and communications capabilities for Defence.

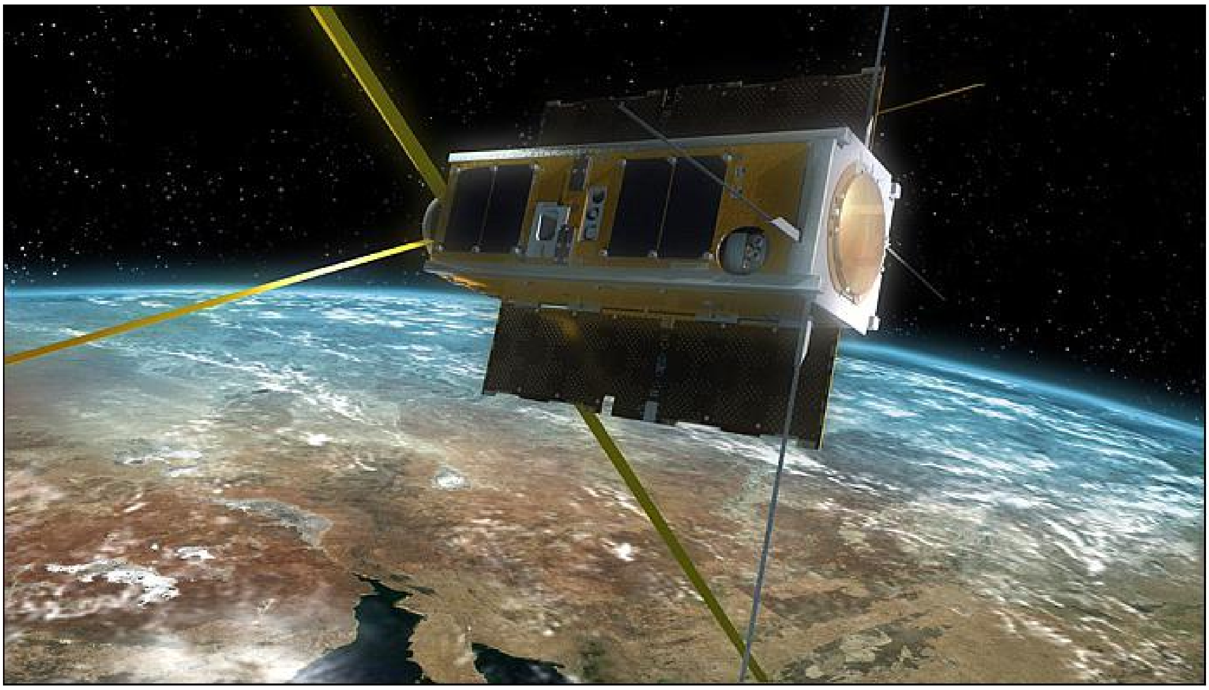

Figure 2: Artist's impression of the initial Buccaneer mission, successfully launched in late 2017. This was the first sovereignly-developed defence-science cubesat mission flown by Australia.

Case Study #4 **Reflectarray antennas**

A reflectarray antenna is a directive antenna composed of a free-space feed (such as a horn) illuminating a large planar surface patterned with periodically arranged sub-wavelength structures (such as metal patches of various shapes and sizes over a ground plane). As such, a reflectarray is often described as hybridisation of a reflector antenna and a phased array, where the individual elements are scatterers fed by a free-space wave. The main advantages for satellite applications are the reduced stowage requirements and low deployment complexity of planar panels, as well as a reduced weight compared to a conventional metallic reflector.

The general principle of reflectarray operation is based on the fine localised phase control of the reflected wave, offered by the individual scatterers on the planar surface. While reflectarrays intrinsically exhibit a narrower operation bandwidth than reflectors, their design offers additional design flexibility that can be harnessed for specific purposes. While a typical configuration can mimic a parabolic reflector profile from a planar surface, more advanced functionalities include directive beams with shaped contours for illumination of a particular Earth region, specific beams tailored to individual frequencies or polarisations, or diplexing abilities in multi-feed configurations. Related concepts include the so-called “metasurfaces” made of deeply sub-wavelength resonators, and the array lenses or “transmitarrays” operating in transmission mode.

Related research activities at the University of Adelaide are dedicated to reconfigurable reflectarrays, where the reflection phase profile of the planar surface can be dynamically tuned using varactor diodes or MEMS components. This opens promising perspectives in adaptive beam shaping. Further research activities concern the translation of reflectarray design principles into the terahertz range to support communications within a satellite constellation, or to create engineered quasi-optical components such as polarisers, wave-plates, polarisation beam-splitters or focussing mirrors.

References

Ref 1 Signal Processing for High Throughput Satellites: Challenges in New Interference-Limited Scenarios, Ana I. Perez-Neira, Miguel Angel Vazquez, M. R. Bhavani Shankar, Sina Maleki and Symeon Chatzinotas, IEEE Signal Processing magazine, Vol.36, Iss. 4, July 2019

Ref 2 https://www.statista.com/statistics/264472/number-of-satellites-in-orbit-by-operating-country/, accessed 09/03/20

Ref 3 Union of Concerned Scientists Satellite Database, https://www.ucsusa.org/resources/satellite-database, December 16 2019 update, accessed 09/03/2020.

Ref 4 “Starlink: SpaceX's satellite internet project”, Adam Mann, Space.com, January 17, 2020. https://www.space.com/spacex-starlink-satellites.html, accessed 09/03/20.

Ref. 5 A. Pereira, S. Al-Sarawi, N. Weste, D. Abbott, J. Kuhn, V. Carrubba and R. Quay, "X-band GaN HPA with integrated supply modulator for airborne applications," IEEE Radar Conference 2018 (RadarConf18), Oklahoma City, OK, 2018, https://doi.org/10.1109/RADAR.2018.8378716

Ref. 6 eoPortal Directory: Buccaneer CubeSat Mission: https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/buccane-1