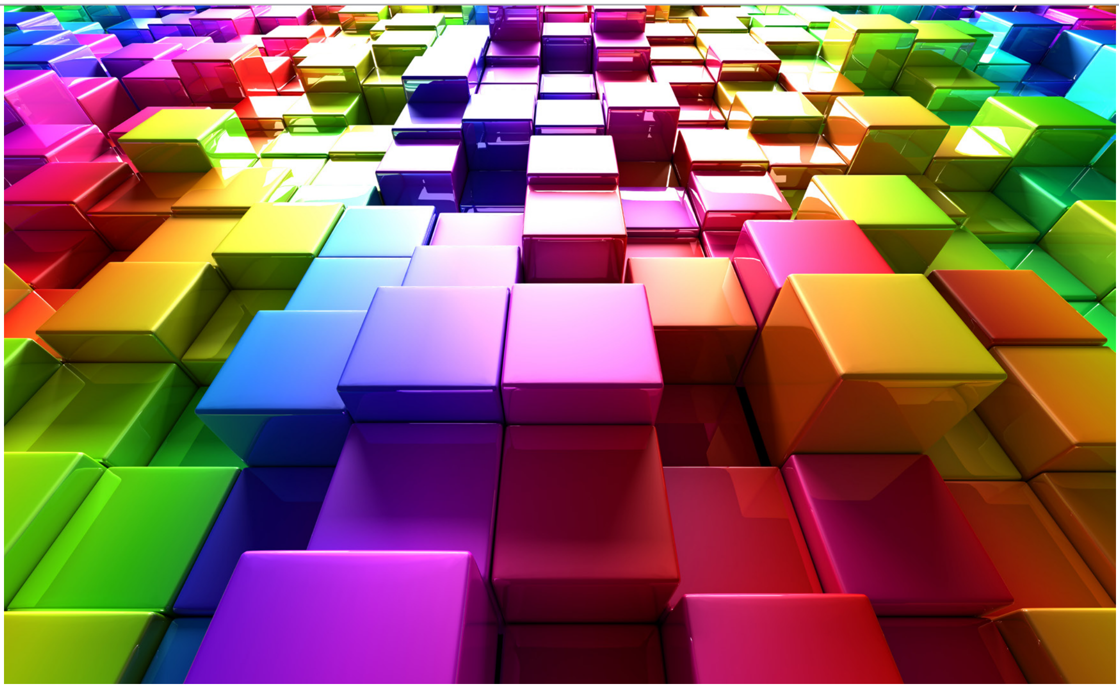


Future Cubesat swarms pose significant communications challenges

Cubesat swarms are innovative and economical small satellite constellations that provide improved autonomous spatial and temporal resolution of targets. Cubesat swarm communication systems bring significant benefits, such as interoperability, higher data rates, bandwidth redundancy, rich power budget, reduced mission failure rates, and the ability to obtain global coverage and measurements. But they also pose prominent challenges in the form of mass, volume and power constraints, limited data rates, and standardisation of frequency licensing policies. In this article, the authors suggest inter- and intra-swarm communication architecture based on a Cubesat swarm low-Earth orbit (LEO) mission with four main types of data link.

Ozan Kara
PhD student, Koç University, Istanbul, Turkey

Roger Birkeland
PhD student, Norwegian University of Technology & Science, Trondheim, Norway

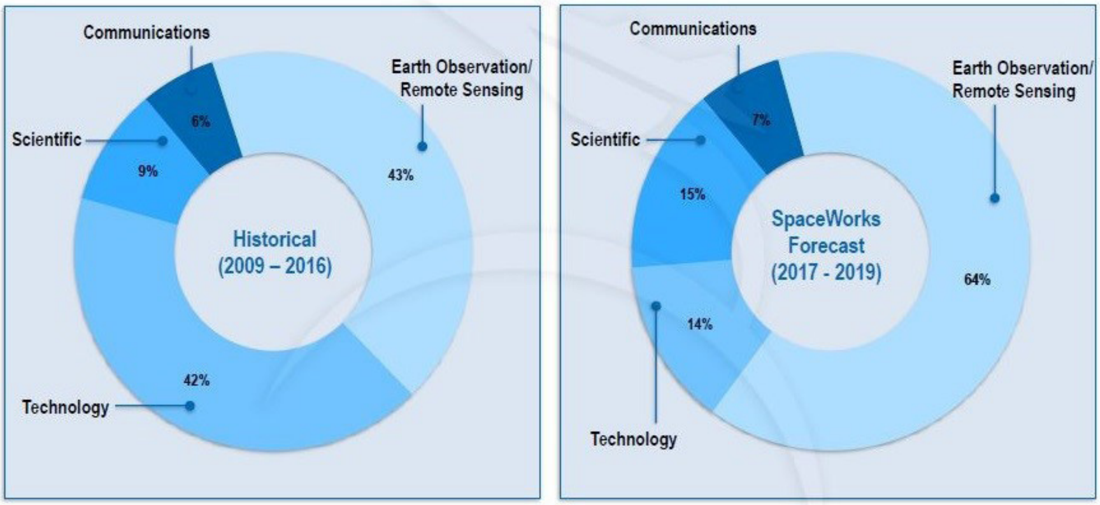
Lihui (Lydia) Zhang
Postgraduate student, Northampton, Massachusetts, USA

Umuralp Kaytaz
PhD student, Koç University, Istanbul, Turkey

Increasing demand for small satellite constellations requires efficient communication architectures in science missions such as gravity mapping, tracking forest fires, finding water resources or detecting vector diseases on the Earth.

There is an emerging trend towards using Cubesats to perform educational, scientific and observation missions thanks to their low cost and easy production opportunities. SpaceWorks Enterprises Inc. provides details of the latest observations and trends in the nanosatellite launch market in its 2017 Nano/Microsatellite Market Forecast (see Figure 1). According to data tracked between 2009-2016, 42 percent of produced nano/microsatellites (including Cubesats) were in the 'Technology' category but this shrinks to 14 percent in the SpaceWorks market forecast for 2017-2019 with 'Earth Observation/Remote Sensing' forecast to increase to 64 percent.

Figure 2 outlines SpaceWorks' projections that more than 2,400 nano/microsatellites could be launched in the period up to 2023. The space community is working to reduce the launch cost for nanosatellites. The overall construction cost of a 1U CubeSat (10 x10 x 10 cm) is around US$30,000 and the minimum launch price is US$12,000. Boeing is aiming to drive down launch costs with



◀ Nanosatellite market trends by purpose.

its Small Launch Vehicle (SLV) concept, which could be in service by 2020 and would launch 45 kg payloads into LEO at a planned cost of US$300,000 (around US$7,000/kg) per launch. [2]

Cubesat communication at a glance

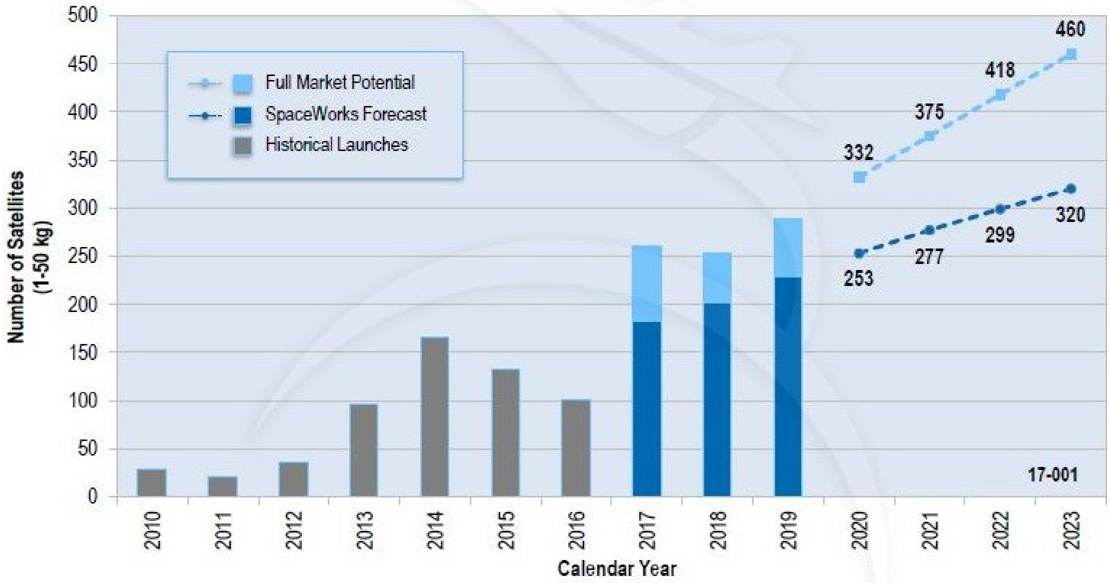
The increasing demand on Earth observation and remote sensing missions via Cubesats requires efficient and flexible communication subsystems and ground stations in order to provide efficient global coverage, collect more data, and optimize downlink time. Currently, most of the Cubesats in LEO use UHF/VHF transmitters with a maximum data rate of around 38 kbps. Only a few Cubesats have S-band transmitters with a maximum data rate of 10 Mbps. In addition, X-band transmitters have around 500 Mbps and K/Ku/Ka band transmitter have up to 1.2 Gbps data transfer rates, but these are more challenging to use with Cubesats. [3]

Technical parameters and constraints

The goal of Cubesat communication architecture is to get as much mission data to the user as possible of various locations of the Earth. In his comprehensive thesis, Ranking Cubesat Communication Systems Using a Value-centric Framework, Clayton Crail states that if we want to maximise the amount of data that is getting to the ground station, we need to increase access time and transmit rate. [4]

Crail also discusses alternative approaches such as using more ground stations and satellite cross-link with network topologies in order to maximise the data gathering. The requirement for more ground stations is rather simple and easy to control. However, more ground network implies new regulations. This requirement also has initial setup costs accompanied with the need for additional staff and while the satellite cross-

There is an emerging trend towards using Cubesats to perform educational, scientific and observation missions thanks to their low cost and easy production opportunities



◀ Nanosatellite launch history and forecast.

link option increases access time, one ends up with several technical challenges such as beam handover, Doppler shift, need for directional antenna, free-space loss and reduced data rate. [4]

Antenna gain is another key parameter for an efficient CubeSat communication network. High gain antenna provides high volume data transfers. Directional antenna gain is the ratio of power density with directional antenna to power density to isotropic radiator with the same total radiated power. In addition to directional antenna, Andrew Kennedy studied bi-directional antenna systems for Iridium and Globalstar missions [5] in order to increase the performance of CubeSat Swarm communication and Scott Schaire discussed alternative types of antenna in his paper, CubeSat Communication and Frequency Past Practice and Current Trends [6] such as standard patch antennas for X and S bands, deployable antennas developed by Boeing, inflatable antennas developed at MIT and Ka-band array with 100 Mbps data rate developed for ISARA. There are also innovative smart antenna designs by Zanette et al [7] that provide good solutions for Cubesats.

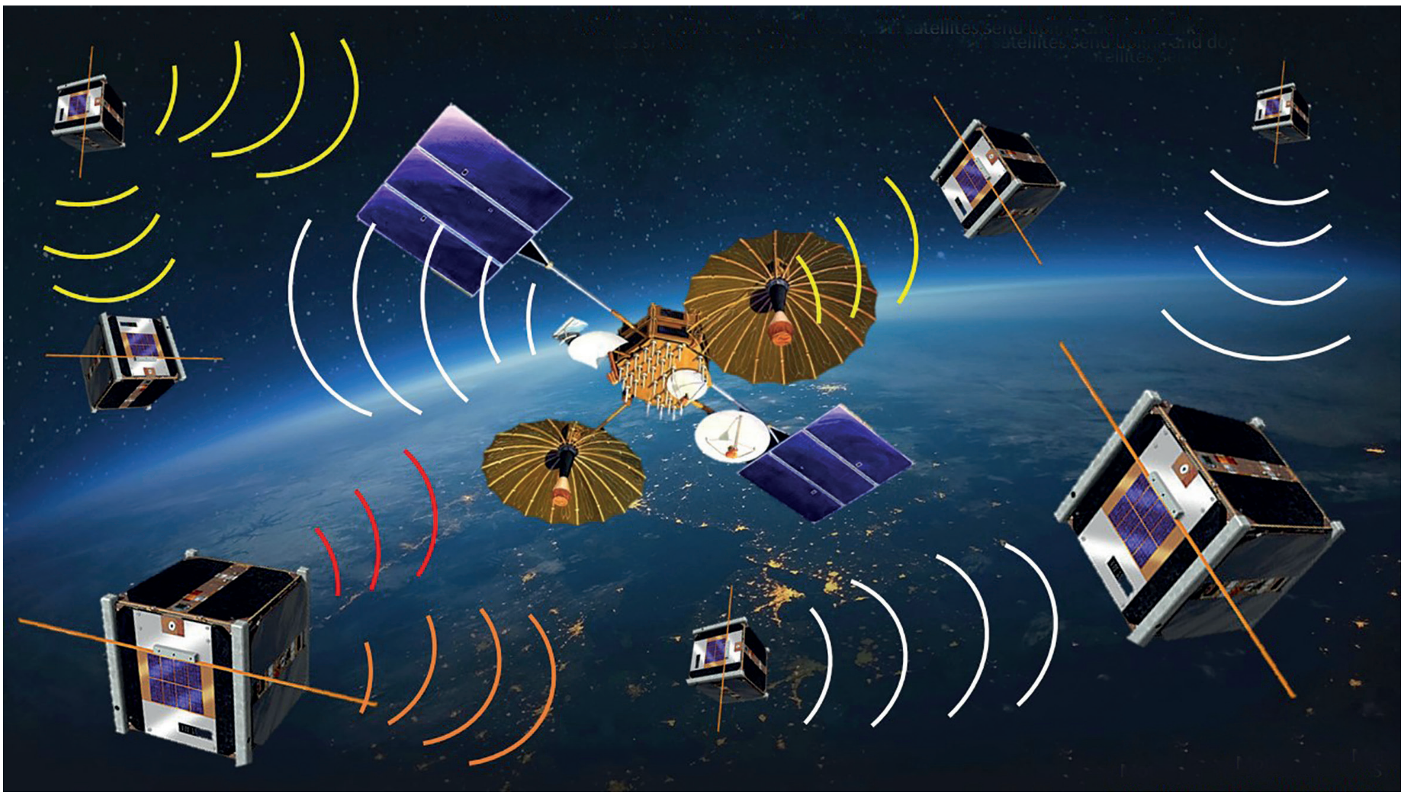
Intra-swarm refers to Cubesats that form a single swarm of small satellites in orbit

Single versus swarm

A swarm of Cubesats in LEO demonstrates advanced cross-link and downlink communications as a low-cost architecture and versatile science platform. A single spacecraft has several disadvantages in comparison with swarm architectures such as limited coverage, unvarying time measurements, limited upgradability and high unit cost. A swarm, on the other hand, provides time correlated measurements, redundant reliability, time varying measurements, scalable coverage of the Earth, flexibility and low single-unit cost with a scalable communication system [8]. Swarm architecture also increases the re-visit rates to ground networks over Earth's surface, which provides geographically dispersed measurements.

Cubesat swarm mission concepts

Several swarm mission concepts have been proposed using nanosatellites. The ARMADA and HiDEF missions were proposed in NASA's 2009 Heliophysics missions to study small scale plasma physics in the ionosphere/thermosphere. The ARMADA mission proposes a swarm of 20 to 100 spacecraft in pseudo-random orbits featuring GPS receivers with radio occultation. HiDEF was designed with 90 swarm spacecraft of low Earth polar orbits in order to monitor electric field and thermosphere density of the auroral Lower-Thermosphere-Ionosphere region [9]. The eLISA mission has been designed by ESA to detect gravitational waves. The mission consists of one 'mother' and two 'daughter' satellites that would be



▼ Intra-swarm architecture artist's concept.

deployed in three different orbits. Communication between the mother spacecraft and ground stations will be performed by X-band links [2].

In addition to these proposed concepts, there are several functional Cubesat swarm missions such as EDSN (Edison Space Network) and Iridium. EDSN consists of a swarm of eight Cubesats at 450-550 km in LEO. Each spacecraft collects space weather data crosslinked to each other via UHF band at a rate of 9.6 kbit/s. [2] After the crosslink, a single spacecraft 'mothership' transfers science data to the ground station using S-band. The Iridium features 66 operational satellites in six planes of 11 spacecraft each in polar LEO at 780 km altitude. [5] Each payload has a data rate up to 100 kbit/s for 90 percent of orbit, and < 1 Mbit/s for the remaining 10 percent. [10]

Frequency selection and licensing

While educational and scientific CubeSat missions generally use UHF amateur radio frequencies, high-performance and military CubeSats use higher frequencies for communications. Universities and non-federal entities prefer to use amateur radio frequencies for Cubesats due to low cost, simpler regulatory processes, and shorter lead times. There is a trend of increasing carrier signal frequency and data transfer speeds due to precise measurements in LEO Earth observation and remote sensing missions. As the frequency increases from UHF to Ka-band, the potential for higher data rates also increases and the potential for absorption by the atmosphere increases. [6]

Government-funded Cubesats that use amateur radio frequencies in the United States may violate the intent of the amateur radio service and go against the rules of the National Telecommunication Information Administration (NTIA) [6]. The National Science Foundation (NSF) has carried out research to find a suitable government frequency band for Cubesats and it is possible that X-band could fulfill the need of efficient modulation and encoding schemes for Cubesats. [6]

LEO intra-swarm architecture

In order to provide sustainable communications, an intra-swarm constellation must first be considered and analysed. Intra-swarm refers to Cubesats that form a single swarm of small satellites in orbit. Within a registered swarm, there will be one mother satellite that is slightly larger with greater capabilities than the daughter satellites and will act as a trunk provider for communications with various ground stations on Earth, as shown in Figure 3.

Individual Cubesats will communicate with each other and with the trunk provider by utilising traditional radio frequency links, but the trunk provider will utilize free-space optical communications that have "become more and more interesting as an adjunct or alternative to radio frequency communications". [12]

Intra-swarm technical issues

The optical communication is considered within intra-swarm architecture that enables larger bandwidths, reduces spectrum and security issues, and fulfills a need for high-speed and reliable communications. The optical communication can be handled by a larger mother satellite until the technology in Cubesats are able to handle these demands. In addition, the performance of the optical communication suffers from strong fading as a result of index-of-refraction turbulence and encounters obstructions from clouds, snow, and rain through the atmosphere [12].

LEO inter-swarm architecture

The larger inter-swarm communication network for LEO CubeSat missions can considered as a 'swarm of swarms'. Inter-swarm refers to the collection of various swarms of Cubesats that are in orbit around the Earth at one time, as shown in Figure 4.

This swarm of swarms network architecture will rely on space-based relay communications using optical communication links and/or radio frequency communication links between the trunk providers of each swarm and the various ground stations established on Earth. Therefore, every CubeSat in orbit must be registered within a swarm in order to access the network.

Delay-tolerant networks (DTN) are recommended within the inter-swarm architecture in order to minimise the loss of data and make the current links more reliable. A DTN is time independent and is designed to operate effectively over extreme distances, such as communicating to a swarm of satellites in orbit from the ground.

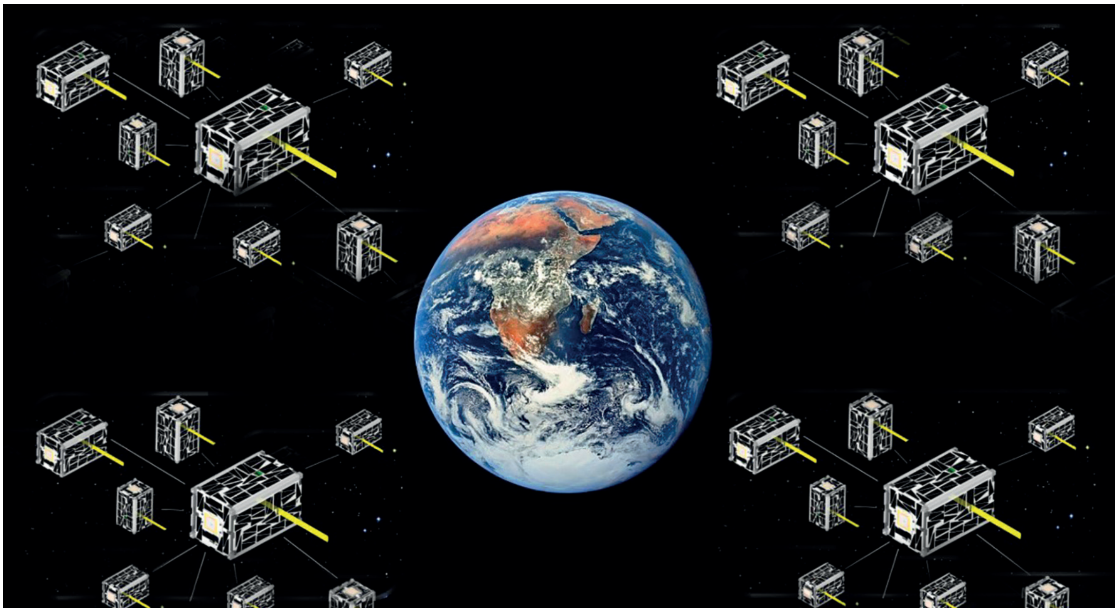
Last words for intra- and inter-swarm

The various technological recommendations discussed ranging from inter-swarm and intra-swarm constellations to optical communications and DTN networks will enable the necessary policies to be put into place in order to maintain and standardize the communication issues of CubeSat swarms in orbit.

Four-segment architecture

The proposed communication network architecture for Cubesat swarms consist of four main types of data links: Cubesat to Ground, Swarm to Ground,

The larger inter-swarm communication network for LEO Cubesat missions can considered as a 'swarm of swarms'



▶ Intra-swarm architecture artist's concept.

Standardisation is essential for maximising compatibility, interoperability, safety, repeatability and quality of the system.

Cubesat to Cubesat, and Swarm to Swarm as stated in Figure 5. The Cubesat to Cubesat data link exists between the various satellites or nodes within a swarm. The Swarm to Swarm data link is primarily formed between the mother or special hub satellites of separate swarms in order to enable inter-swarm communications.

Although the mother satellites will act as the primary uplink and downlink source to the ground stations on Earth through the Swarm to Ground data link, individual Cubesats of a swarm also have the capability to transmit and receive data from ground stations through the Cubesat to Ground data link when necessary. Every Cubesat within the global network can be assigned an identification number. The main network is comprised of several ground stations. Then, multiple Cubesat swarms consisting of smaller individual networks (within each swarm) can be analogous to the structure of the Internet. Essentially, there can be an infinite number of satellites and ground stations that can enter and gain access to the space network similar to how a newly produced electronic device can gain access to the Internet as long as the service is paid for or as long as it uses the wireless network.

Identification and standardisation

The Space Generation Advisory Council (SGAC) working group 'Cubesat Swarms – Communication Networks and Policy Challenges' has recommended that the CubeSat swarm network adopt a similar architecture to the Internet in which each Cubesat within the network has a unique address. With this suggestion, the Interagency Operations Advisory Group (IOAG) and the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) should be considered as entities who could standardise the space network protocols along with the assignment of a network address to a particular Cubesat.

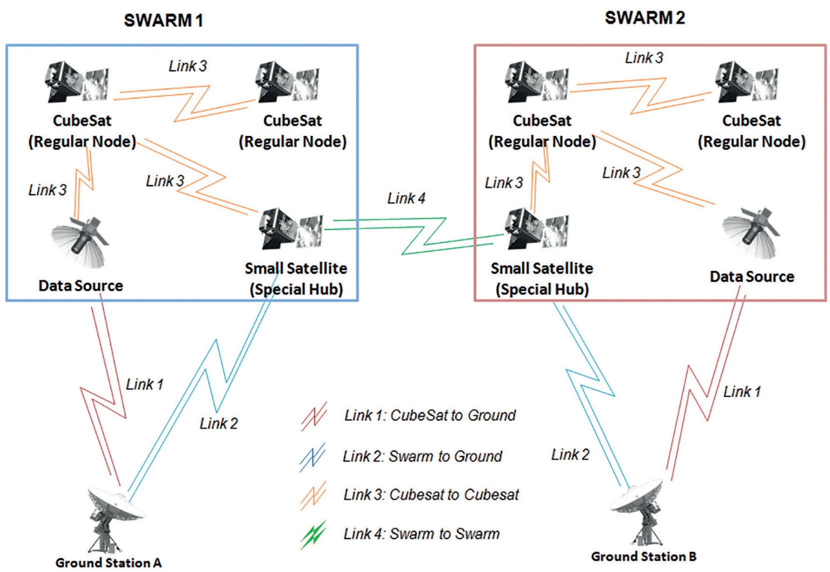
Standardisation is essential for maximising compatibility, interoperability, safety, repeatability and quality of the system. The working group offered that each Cubesat within the global network should be assigned an identification number and satellite operators are expected to adhere to network requirements. Operators also expect streamlined registration, high downlink speeds, and equal priority for data transfers.

The working group also proposed setting up a network whereby a user can register their unit to gain access. This would be very similar to the architecture that a smartphone uses when connecting to wifi; a user would enter their password and hop on a network to gain access to their Cubesat. This would greatly reduce registration time and alleviate the burdens that come with filing satellites.

Things to consider

High-rate communication for CubeSat swarm missions could revolutionise Earth observation. Optical communications could enable applications that need high bandwidth. The subsequent goal for the optical downlink could be 100 Mbps that in comparison data from the Mars orbiter sent back at a rate of 6 Mbps. Cubesats could use X-band in order to reduce the size and mass of the transceiver. Smart-antenna array could also be significant technologies for more efficient data downlink.

It is important to design a communication system for higher data rates with the same power consumption of Cubesats. Another significant factor is atmospheric losses. Low-orbiting Cubesats experience losses ranging from a minimum when the satellite is directly above the ground station to a maximum loss when the satellite is only visible at low altitudes above the horizon. In such worst-case conditions, the signal travels at a more acute angle with respect to the horizon and is subjected to more atmospheric losses. Therefore, inter- and intra-satellite links are key considerations for the success of swarm missions. The proposed communication scheme can combine RF and optical communication and power-efficient modulation. This approach is also considered as unscheduled multiple access that could be seen as 'common architecture' for swarm missions. ■



▲ Main four segment CubeSat swarm architecture concept.

About the authors

Ozan Kara received a BSc from Istanbul Technical University Astronautical Engineering department on CubeSat Moon Mission Design. His MSc at Koç University Mechanical Engineering Department focused on Small Satellite Moon Mission Optimization by using Electric Propulsion Systems. He is currently a PhD candidate at Koç. Ozan is the Space Generation Advisory Council (SGAC) National Point of Contact in Turkey. He is also a member of several International Astronautical Federation (IAF) and American Institute of Aeronautics and Astronautics (AIAA) committees.

Roger Birkeland is a PhD student at the Norwegian University of Technology and Science (NTNU), studying the use of small satellites in future sensor networks. He holds a Master's degree in electronics from NTNU, having majored in satellite communications. He has previously worked with embedded systems and underwater communications, before leading a student satellite project at NTNU.

Lihui Lydia Zhang holds a Bachelor's degree in astronomy and economics from Smith College, Massachusetts, USA. She is interested in the intersection between space technology and social science, and is currently pursuing further education in these fields.

Umuralp Kaytaz received his BSc degree in electrical and electronics engineering from Koç University, Istanbul, Turkey, and his MSc degree in computer science from the University of Warwick, UK. He is currently working towards his PhD in electrical and electronics engineering with the Wireless Networks Laboratory in Koç University.

References

1 http://spaceworkseng.com/spaceworks-releases-2017-nanomicrosatellite-market-assessment/

2 R. Radhakrishnan, W. W. Edmonson, F. Afghah, R. M. Rodriguez-Osorio, F. Pinto and S. C. Burleigh. Survey of Inter-Satellite Communication for Small Satellite Systems: Physical Layer to Network Layer View; IEEE Communications Surveys & Tutorials, vol. 18, no. 4, pp. 2442-2473, Fourth quarter 2016.

3 Small Spacecraft Technology State of Art, Mission Design Division Staff, NASA Ames Research Center, NASA/TP–2014–216648/REV1, July 2014.

4 Crail, B. Clayton. Ranking CubeSat Communication Systems Using a Value-centric. Framework; MBA and MSc in Aeronautics and Astronautics Thesis, MIT, June 2013

5 Kennedy, Andrew Kitrell. Resource Optimization Algorithms for an Automated Coordinated CubeSat Constellation; MSc in Aeronautics and Astronautics Thesis, MIT, August 2015.

6 Schaire, Scott. CubeSat Communication and Frequency Past Practice and Current Trends; NASA Goddard Space Flight Center, June 2014.

7 Zanette, Luca; Reyneri, Leonardo; Bruni, Giuseppe. Communication and Mutual Physical Position Estimation System for CubeSat; 8th European CubeSat Symposium, londra, 7-9 September 2016. pp. 57-58.

8 EDSN: Edison Demonstration for SmallSat Networks Overview, Small Spacecraft Technology Program, Space Technology Mission Directorate, NASA.

9 Spangelo, Sara C. Modeling and Optimizing Space Networks for Improved Communication Capacity; PhD Thesis, University of Michigan, 2013.

10 https://directory.eoportal.org/web/eoportal/satellite-missions/i/iridium-next.

11 Kara, Ozan, et al. Communication Architecture and International Policy Recommendations Enabling the Development of Global CubeSat Space Networks. International Astronautical Congress 2015, IAC2015 Jerusalem, Israel.

12 Henniger, H., Wilfert, O. An Introduction to Free-space Optical Communications. Radioengineering, Vol 19, No. 2, June 2010, pp 203-212.

13 Schier, James. Future of Space Communication. Human Spaceflight Knowledge Sharing Forum, NASA Space Communications and Navigation, November 2016.

Space Generation Advisory Council

ROOM offers members of the Space Generation Advisory Council (SGAC) a forum in the form of a regular article in which to provide their insight and inputs on various space topics, from technical projects to regional perspectives.

SHAC is an international non-profit, non-governmental organisation, formed out of the Vienna Declaration, adopted by the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNI-SPACE III) in 1990, which recognised the need to engage with the next generation of space leaders and reflect the voice of students and young professionals in space policy.

Since then, SGAC has grown to support students and young professionals, not only organising global, regional and national events and providing a medium for them to share their insights on space policy, but also enabling their professional development through volunteer opportunities, scholarships and competitions to attend conferences and events.