On Information Technology Issues in the Nanosatellite Era

Manfred Sneps-Sneppe, Romass Pauliks
Ventspils University of Applied Sciences, Latvia
Ventspils, Latvia
manfreds.sneps@gmail.com, romass.pauliks@venta.lv

Dmitry Namiot
Lomonosov Moscow State University
Moscow, Russia
dnamiot@gmail.com

***Abstract*—The paper is an interpretation of the research on the Internet of Things in the context of scientific interests of Ventspils International Radio Astronomy Center (VIRAC). A nanosatellite essence has been explained as well as data on nanosatellite launches with forecasts are given. Digital Video Broadcasting DVB-S2 basics and some nanosatellite (so-called CubeSat) features are given. Some emergence nanosatellite researches regarding information technologies have shown, namely, Inter-Satellite Communication, and MAC Protocol studies. In the Section on CubeSat teaching, we consider the US University Nanosat Program and the European Space Agency efforts, considering in more detail the OPS-SAT tools – a CubeSat developed as a training platform.**

I. Introduction

The paper is an interpretation of our research on the Internet of Things [1] in the context of scientific interests of Ventspils International Radio Astronomy Center (VIRAC). What is the VIRAC about?

VIRAC is the only radio astronomy (RA) research center in the Baltic States located in Latvia. Irbene radio antenna complex had founded in 1967 as a secret Soviet astronomy and communications center (military object "Zvezdochka") to spy on West communications. Irbene is located 30 km north of Ventspils (Latvia) on the coast of the Baltic sea. VIRAC was founded in 1994 after the transfer of the Russian Federation's military unit. VIRAC was included in the Ventspils University of Applied Sciences (VUAS) as the scientific institute. The fully rotating 32-meter parabolic RT-32 antenna is the largest one in northern Europe [20]. Both antennas RT-32 and RT-16 had restored in 2015 (Fig. 1).

Fig. 1. VIRAC radio telescopes RT-16 and RT-32

Besides, VIRAC owns two LOFAR antenna arrays low band – 30 MHz and high band – 120 MHz, respectively, both having 96 dipoles (Fig. 2). Because of the very low level of radio interference, this site perfectly is suitable for the sensitive LOFAR radio telescope [3].

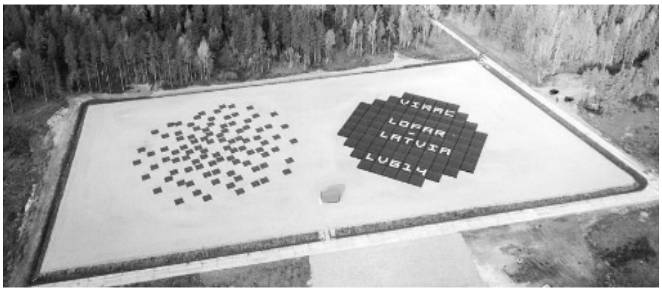

Fig. 2. LOFAR – Latvia LV614 [16]

VUAS had some experience in the nanosatellites area also (Fig. 3). Venta-1, Latvia's first artificial satellite, was built by the University of Applied Sciences, Bremen, Germany for Latvia under the contract with VUAS and VATP Latvia and the assistance of VUAS students. The signals aired by the satellite are received at the Ventspils International Radio Astronomy Center.

Venta 1 is a Latvian nanosatellite. It is equipped with a low-resolution ground surveillance camera and automatic identification system (AIS) receivers for tracking vessel movements in Europe. The satellite carries a LuxSpace receiver as its primary payload. The AIS data are downloaded via a S-band frequency link. The satellite is attitude controlled via magnetic torquers around three axes and stabilized by a slow rotation around the sun generator axis pointing to the Sun [4].

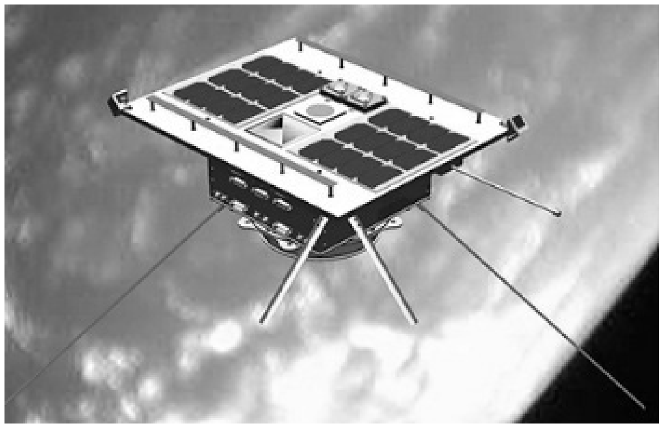

Fig. 3. Venta-1 – Latvia's first artificial satellite

The VIRAC's key goal today is the re-equipment of radio telescopes RT-16 and RT-32 for space communication. The adaption of RT-16 for nanosatellite ground station needs is going on. The aim of the project is to re-equip RT-16 in order to support nanosatellites operating in S-band (2.2–3.4 GHz), C-band (5.8 GHz), and X-band (8.2–10.5). The project is going on in co-operation with the Swedish National Space Agency and under European Space Agency support.

The aim of the paper is to discuss the VIRAC nanosatellites strategy issues. The content is the following. Section 2 explains a nanosatellite (so-called CubeSat) essence. In Sections 3 and 4, the satellite communications basics and some nanosatellite features are explained. In Sections 5 to 7, some information technology actual research issues in the nanosatellite era are given, namely, MAC Protocol, and Inter-Satellite Communication studies. Section 8 is devoted to CubeSat teaching with the emphasis of OPS-SAT – a CubeSat developed as a training platform.

II. WHAT IS NANOSATELLITE ABOUT

Nanosatellites are defined as any satellite weighing less than 10 kilograms. They all are based on the standard CubeSat unit, namely a cube-shaped structure measuring 10x10x10 cm with a mass of somewhere between 1 and 1.33 kg. This unit is known as 1U. By multiplying this modular unit, the larger nanosatellites are now common: from 1U to 12U (Fig. 4).

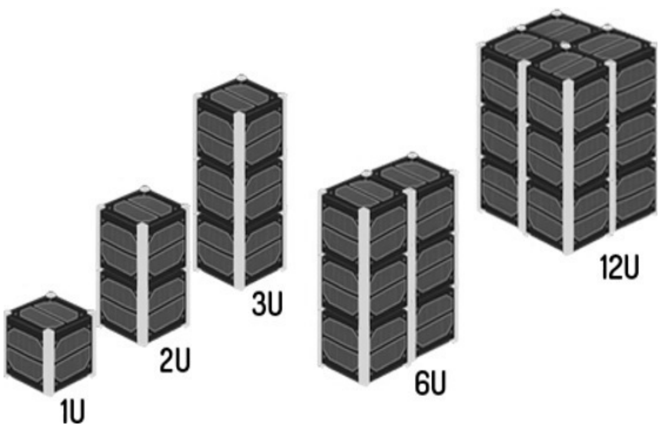

Fig. 4. A series of CubeSats

The satellite field in LEO orbit has grown rapidly in recent years (Fig. 4). Newly proposed concepts are highly ambitious [2]:

(i) The OneWeb constellation is initially expected to comprise 882 small Internet service delivery satellites in low orbits. It should grow later up to 2600 satellites.

(ii) The constellation of 4600 satellites, according to forecasts by Samsung, will have to provide the transfer of one billion terabytes of data per month.

(iii) The SpaceX's Starlink satellite constellation will include up to 12,000 small satellites in low orbits, which will be able to serve 10% of local Internet traffic in densely populated areas.

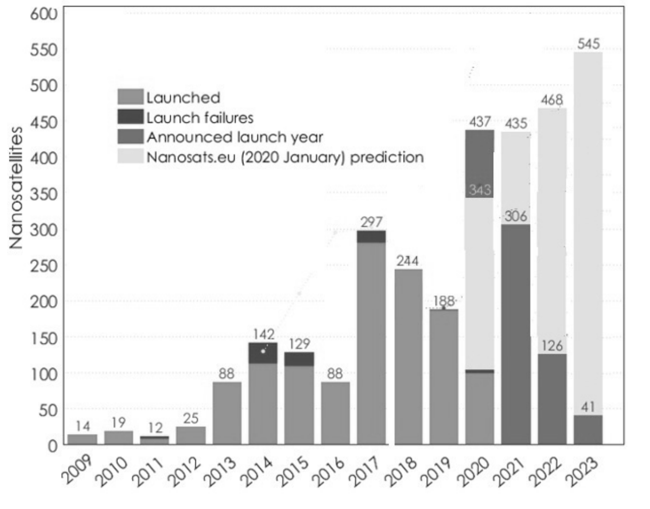

Fig. 5. Nanosatellite launches with forecasts (the excerpt from https://www.nanosats.eu)

As a nanosatellite case, we consider BRITE-Constellation [6]. BRITE (BRIght-star Target Explorer)/CanX-3 (Canadian Advanced Nanosatellite eXperiment-3) is an Austrian/Canadian constellation of nanosatellites (Fig. 6). The objective is to make photometric observations of the stars in the sky. According to the design documentation, the accuracy of such observations should be at least 10 times better than the accuracy of ground-based observations.

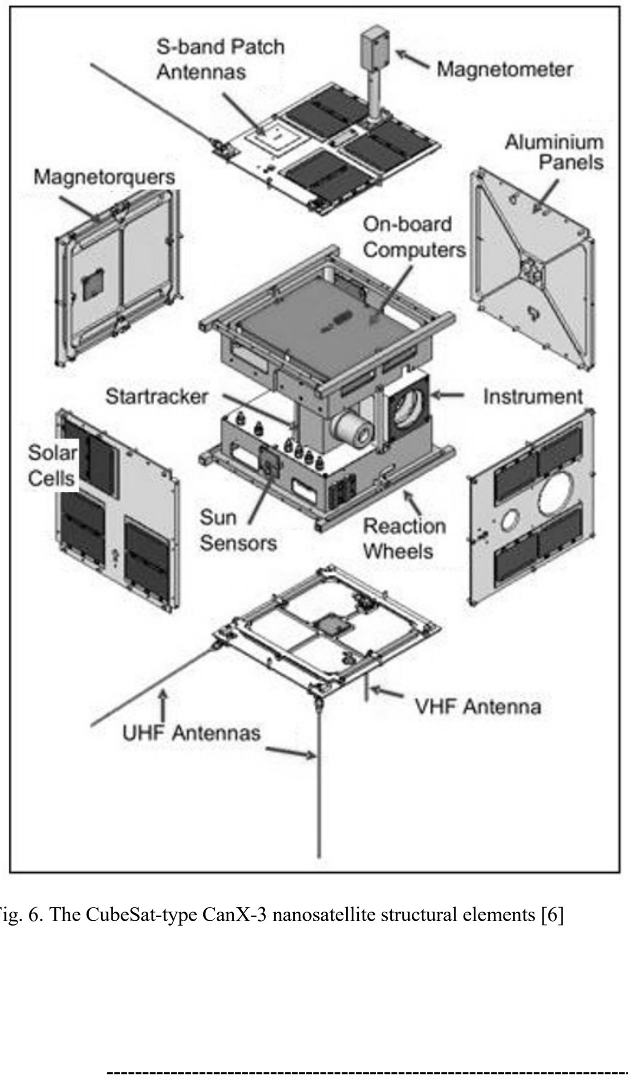

Fig. 6. The CubeSat-type CanX-3 nanosatellite structural elements [6]

BRITE RF communications parameters are the following:

downlink (S-band) data rate – 32 to 256 kbit/s,
uplink (UHF) data rate – up to 4 kbit/s,
data volume/day – 2 MByte (typical),
S-band frequency – 2234.4 MHz, transmit power – 0.5 W,
UHF-band frequency – 437.365 MHz,
VHF beacon – 145.89 MHz, transmit power – 0.1 W

III. SATELLITE COMMUNICATIONS BASICS

The satellite communications scheme shown in Fig. 7 slightly differs from the nanosatellite case, namely, instead of users, there are sensors with the restricted channel capabilities: the key objectives of nanosatellites is to collect data from IoT sensors.

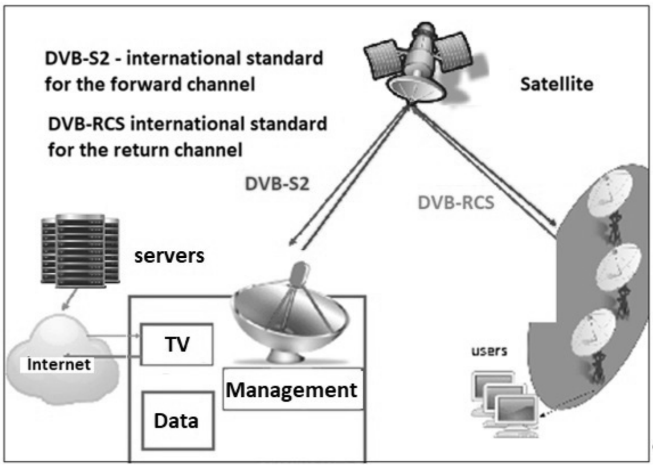

Fig. 7. Satellite communications scheme [7]

The nanosatellite concept is basically following Digital Video Broadcasting standards [7]. DVB-S2 main features are the following (Fig. 8):

- A powerful FEC (Forward Error Correction) system based on LDPC (Low-Density Parity Check) codes. A wide range of 11 LDPC code rates is used: from 1/4 up to 9/10;
- 4 constellations (QPSK, 8PSK, 16APSK, 32APSK) are ranging in spectrum efficiency from 2 bit/s/Hz to 5 bit/s/Hz (Fig. 9);
- A set of three spectrum filter shapes with roll-off factors 0,35, 0,25 and 0,20;
- Adaptive Coding and Modulation (ACM) functionality, optimizing channel coding and modulation on a frame-by-frame basis.

FECFRAMEs are 64,800 or 16,200 bit sequences (normal or short FECFRAME). FECFRAME shall be serial-to-parallel converted by coding schemes: 2 bits for QPSK, 3 – for 8PSK, 4 – for 16APSK, 5 – for 32APSK. Provided that with 11 coding rates and four modulations order available, there will be 44 possible combinations. Only 28 of them are included in DVB-S2 standard [7]: from MODCOD 1 – QPSK-1/4 to MODCOD 28 – 32APSK-9/10. The LDPC decoder was set up to 50 iterations at a normal frame size (64,800 bits), requiring a lot of computing power.

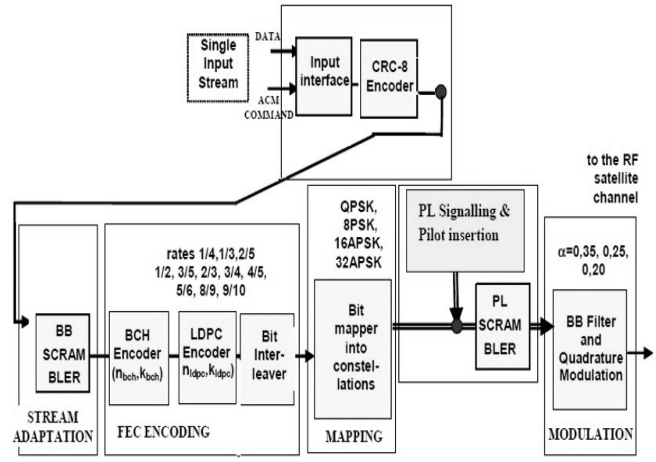

Fig. 8. Functional block diagram of the DVB-S2 System (the excerpt from [7] for a single input stream).

ACM techniques are an option for performing the link adaptation into the changing environmental conditions. The best MODCOD in terms of throughput maximization should be selected. One of the main drawbacks of applying ACM techniques in satellite communications is the high Round Trip Time (RTT). This does not allow have a reliable estimation of the channel parameters, especially in mobile scenarios.

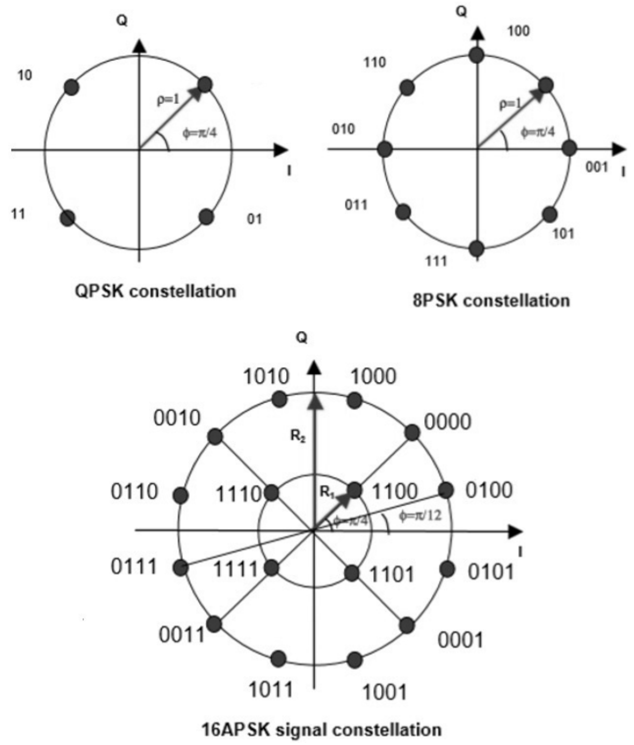

Fig. 9. Bit mapping into signal constellation [7]

IV. NANOSATELLITE FEATURES

Small satellites are usually located in low-earth orbit (LEO) (200 – 2,000 km). The speed of the satellites in LEO (relative to Earth's surface) is around 7.5 km/s, which is an orbital period of approximately 90 min. Therefore, the Doppler shift and short communication windows are a significant matter for communication using small satellites. The small volume of the satellites limits the size of the battery. This reduced volume also limits the surface area and the total area for solar panels, which affects the amount of power generation [8].

For example, the CubeSat for precipitation monitoring in [9] generates a daily payload of 1.73 Gb, while the available data rate is 50 kbps. The transit period is 10.8 minutes (for an altitude of 450 km). At this speed, a whopping 53 passes would be required to offload payload data, which uses a distributed network of 25 ground stations.

IoT is primarily for device-to-device (D2D) communication. IoT (M2M) systems have their own specifics compared to mobile communications. The IoT requires more connected devices and low power data transmission due to the limited power of the end device. At the same time, a lower transmission rate is possible in the IoT. The satellite communication system uses a 400 MHz band for half-duplex communications with a 100 kbps maximal data rate. These frequencies are in the range of used amateur frequencies, and this band has low propagation loss compared to satellite broadband. The performance of such systems has been proven in many CubeSat projects deployed to date [9].

V. ON MAC PROTOCOLS FOR NANOSATELLITES: ALOHA

The most representative Medium Access Control (MAC) protocol is Aloha, developed in 1970 [10]. It is a random access protocol and inspired for many others (Fig. 10). This protocol is quite old and simple. Nevertheless, in current IoT developments, Aloha plays a fundamental role. For example, leading IoT technologies like LoRa and SigFox use variations of this protocol. In Pure Aloha, nodes send data when they are ready. When the reception of a packet is successful, the receiver sends an acknowledgment (ACK). In case of a collision, nodes retransmit the same packet after a random time. As such, the protocol does not require prior coordination or additional signaling to control access.

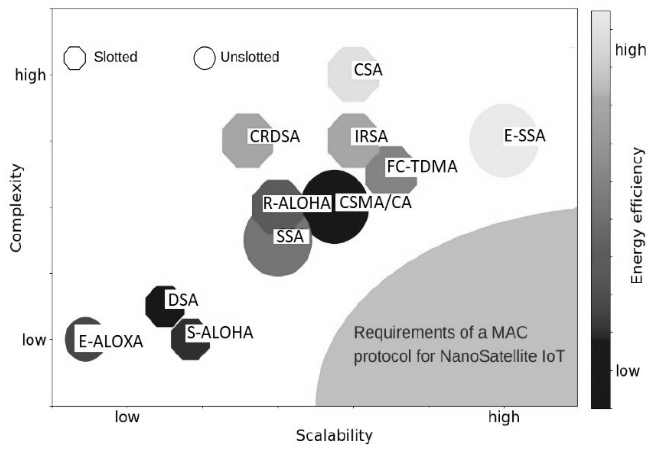

Fig. 10. A comparison of MAC protocols in the context of nanosatellite IoT scenarios. Abbreviations here: (1) Aloha-based protocols: Slotted Aloha, Diversity Aloha/Slotted Aloha, Spread Spectrum Aloha, Enhanced Aloha, Random Frequency Time Division Multiple Access; (2) Reservation and Adaptive Protocols: Reservation Aloha, Carrier Sense Multiple Access with Collision Avoidance, Fixed Competitive TDMA; (3) Interference Cancellation-Based Protocols: Contention Resolution Diversity Slotted Aloha, Irregular Repetition Slotted Aloha, Coded Slotted Aloha, Enhanced Spread Spectrum Aloha.

Fig. 10 shows a comparison of MAC protocols, derived from the IoT scenarios together with the CubeSat restrictions. An ideal performance zone is not yet met by any of the reviewed protocols. How to take into account a low processing capacity demands and a variable and dynamic number of ground sensors and devices? All this requires additional research and is a promising area for work in space communications.

The ease of implementation and minimal hardware requirements make Aloha-based protocols a good choice for the MAC layer in nanosatellites. At the same time, ease of implementation becomes an issue when the number of nodes increases, which is quite expected for IoT projects.

VI. ON MAC PROTOCOLS FOR NANOSATELLITES: AX.25

AX.25 is one much more sophisticated access protocol. AX.25 data link layer protocol is popular for general amateur radio communication and useful in nanosatellite communication also.

Let us refer to nanosatellite UiTMSAT-1 [9]. This case presents the CubeSat concept in more detail. As in any satellite communication, there are three important elements: (1) the space segment, (2) the ground segment, and (3) the mission control segment (Fig. 11).

UiTMSAT-1 is a BIRDS-2 nanosatellite project involving four countries: Japan, Malaysia, Philippines, and Bhutan. The objective of this mission is to collect IoT sensor data by space-based UiTMSAT-1, store them on-boards, and download the sensor data to the Mission Control Centre (MSS). For downloading the satellite's ultra-high frequency (UHF) antenna is used. Fig. 11 shows the illustration of the Store and Forward (S&F) mission by communication between with space-based IoT terminal and MCC.

The ground IoT sensor terminal collects the data from the sensors and should be ready to communicate with the satellite once the satellite approaches the location where the IoT terminal lies. The function of this terminal is to transmit or receive the information to/from the satellites in the most reliable manner while maintaining the desired signal quality.

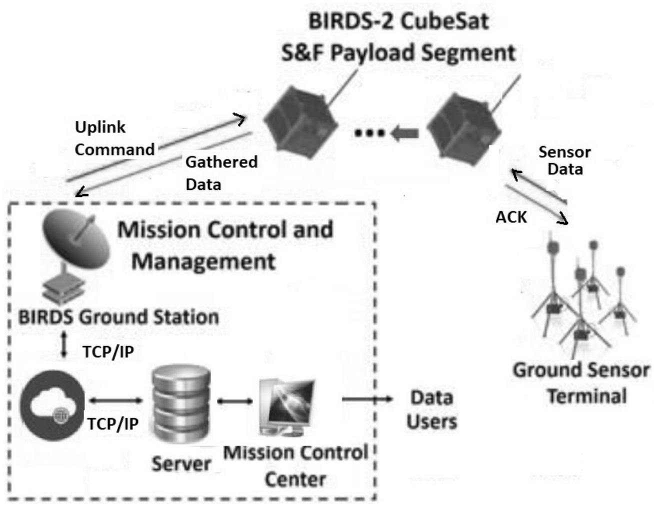

Fig. 11. System architecture of BIRDS-2 S&F nanosatellite-based remote data collection system [6]

Fig. 12 shows the communication layers for the space-based IoT terminal to communicate with the S&F payload. There are several communication layers involved, such as a physical layer, data link layer, and application layer.

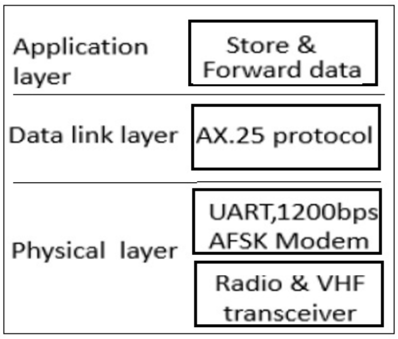

Fig. 12. Communication layers to send the sensor data from the terminals to the BIRDS-2 CubeSat S&F Payload Segment

In the application layer, UiTMSAT-1 will collect S&F data. The AX.25 protocol is used in the data link layer, to accept and deliver the packet sensor data over a communication link. The AX.25 protocol is arranged in a frame the structure of which is shown in Fig. 13. In total, 122 bytes out of 175 bytes are available for IoT data.

	START	DESTINATION CALL SIGN	SOURCE CALL SIGN	CONTROL	PID	INFO FIELD	FCS	END
BYTES	1	2-8	9-15	16	17	18-172	173-174	175

Fig. 13. AX.25 protocol format

The design of future MAC protocols for nanosatellite IoT solutions is one of the open nanosatellites industry challenges.

VII. On Inter-Satellite Communication

Inter-Satellite Communication (ISL), or crosslink, is one important problem but rather far from the acceptable solution. As in M2M interactions, here it is necessary to transfer data between satellites (within a network of satellites) without human participation or with his minimal participation. According to the nanosatellite mission purpose, ISL data could be user IoT data from a ground terminal, operational data, or payload data.

As a case, we consider the SLINK radio developed by the Technical University of Berlin (TUB) [11] in co-operation with IQ wireless (see Table 1). A highly integrated S-band transceiver has developed with a maximum of 169 kbps crosslink capability suitable for nanosatellites.

TUB has developed a resilient S-NET constellation of four satellites. It is designed to test Inter-Satellite Communication and demonstrate its capabilities. The four S-NET satellites were launched on 1 February 2018 by a Soyuz/Fregat launcher from Vostochny Cosmodrome, Russia, into a 580km orbit. This allowed the overall performance of SLINK radio, ISL timing, data routing, and reliability to be tested in a real environment.

TABLE I. Parameters of the SLINK Radio [11]

Parameter	Value
Frequency ISL, DL	2210.2–2269.8 MHz
Frequency UL	2024.2–2109.8 MHz
Range ISL	100 km nominal, up to 800 km
Bit rate DL	0.674–3.394 Mbps
Bit rate UL	30.8–252 kbps
Bit rate ISL	8.8–126.55 kbps (DBPSK, 800 km; 8-ADPSK, 100 km)
Symbol rate ISL	80 kHz
RF bandwidth ISL	120 kHz
Multiplexing	TDD, P2P
Modulation	DBPSK, DQPSK, 8-ADPSK, and 16-ADPSK (optional)
Coding	Convolutional $r = 1/2, r = 3/4$
Decoding	Viterbi, soft decision
RF output	27 dBm (0.5 W)
Power	<12 W
Mass	<450 g with housing
Volume	$140 \times 80 \times 65$ mm^3

The complete communication graph is given in Fig. 14. As you can see from the figure, each pair of nodes can be connected directly. Alternatively, you can use the master node, but in any case, there will be no multi-hop routing. The S-NET mission is, thus, one of the first nanosatellite missions to perform multi-point network communication in orbit.

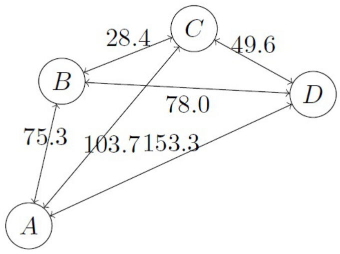

Fig. 14. Graph representation of S-NET nodes (August 2018) with numbers in km [11]

VIII. On CubeSat teaching

Apply to our IoT teaching course survey [1]. The IoT curriculum at the upper level can be represented by the following broad topics:

1. Data measurement (sensing)
2. Data transmission (networking)
3. Data aggregation (middleware)
4. Data analysis
5. Data interaction (behavior).

Therefore, at the first hand, we need to measure (the use of sensors). Then the collected measurement should be transmitted (through of some kind network). In most cases, we will need more than one measurement. Then, we should be able to aggregate the measurements (by middleware tools). As soon as data are collected, we can analyze them (this is the data analysis phase) and make conclusions about some actions (define the behavior). In practical terms, this covers all the basics of designing and using the Internet of Things (M2M).

Let us call a few best practices. The most attractive case comes from the U.S. [12].

Of note is the University Nanosat Program in USA, which is a moderated competition for the design and manufacture of satellites intended for universities. The program is jointly managed by the following five top administrative level institutions:

The Air Force Office of Scientific Research,

The Air Force Research Laboratory,

The American Institute of Aeronautics and Astronautics,

The Space Development and Test Wing

The AFRL Spacecraft Technology.

The aim of the program is to train future specialists in the field of space. To do this, they need to be provided with opportunities for research and development of small satellites, the integration of hardware and software, and for flight tests. Statistics show 4,500+ college and university students who have participated in this program since its launch in 1999.

Many European universities are active in the nanosatellite field as well as supported by the European Space Agency (ESA).

The paper [13] explains the manner in which the development of CubeSat nanosatellites has been integrated into the curricula of Computer Science and Spacemaster – Master's Program in Space Science and Technology at the University of Würzburg. As an example of one of the works under this program, the project of a ground control center for CanSat is given.

For any beginner in the nanosatellite area, it is worth applying to OPS-SAT [14].

The OPS-SAT is a nanosatellite that is solely designed to demonstrate open source satellite and ground control software in real-life flight conditions. This project is being implemented by the European Space Operations Center (ESOC) in Germany. The OPS-SAT is an ingenious design that builds on years of experience gained by ESOC engineers on major missions from the European Space Agency. But the main thing is an open Java framework for onboard software of nanosatellites.

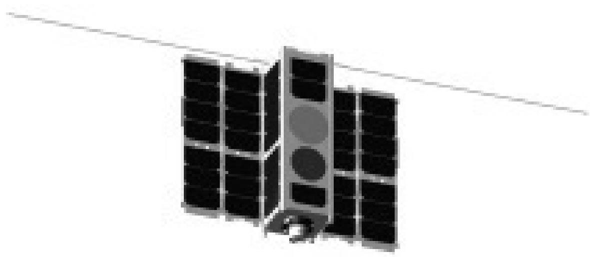

Fig. 15. OPS-SAT Configuration [15]

OPS-SAT is a CubeSat supervised by the European Space Agency. In reality, OPS-SAT is a flying laboratory and intended to demonstrate the improvements in mission control capabilities that will arise when satellites can fly more powerful on-board computers. The satellite features an experimental computer that is ten times more powerful than any current ESA spacecraft [15].

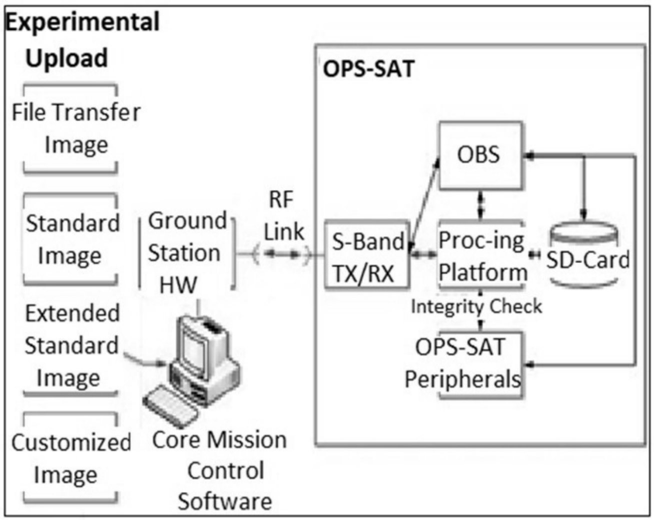

Fig. 16. OPS-SAT File based experiment concept [15]

OPS-SAT will provide a test environment directly in orbit for various field experiments to test new communication protocols, new data processing algorithms, and software integration. One innovative concept is the deployment of space software in the form of applications (Fig. 16).

Overall, this is a completely new concept that ESA wants to test in real-life flights. This concept has no analogues in previous projects. By analogy with Software Defined Networks, it can be called Software Defined Satellite. The concept is enabled by the NanoSat MO Framework (NMF). OPS-SAT has been launched on 18 December 2019. Fig. 17 presents NMF architecture (one application only).

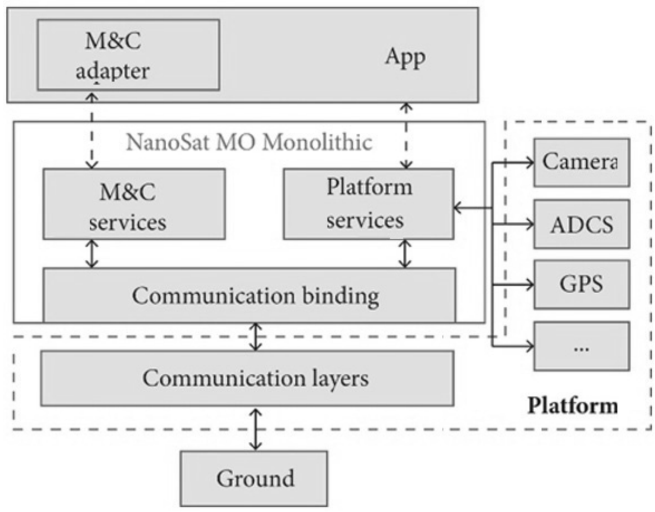

Fig. 17. The simplified NMF architecture [16]

The Experimental Platform in Fig. 17 is the basic testbed. It has two Critical Link MityARM 5CSX in cold redundancy (if one fails, the second one is used). The hardware part contains a Dual-core 800 MHz ARM Cortex-A9 processor, an FPGA, 1 GB RAM, and an external memory device with 8 GB of memory. The software developing tools includes: Linux, Java, CCSDS File Delivery Protocol (CFDP), and NanoSat MO Framework.

The most innovative OPS-SAT concept is a modular approach to space software deployment. Satellite programs can now be developed (launched, updated) as independent applications. The European Space Agency in collaboration with the Graz University of Technology investigated and developed the NanoSat MO Framework (NMF). It is a software framework for nanosatellites based on CCSDS Mission Operations services. It includes a Software Development Kit to develop experiments as NMF Apps, which can then be installed, started, and stopped in space.

We consider OPS-SAT tools as an essential part of CubeSat teaching.

IX. CONCLUSION

The paper is an interpretation of the research on the Internet of Things in the context of scientific interests of Ventspils International Radio Astronomy Center (VIRAC). These are some thoughts about the teaching of information technology students in VIRAC interests.

A nanosatellite essence has been explained as well as data on nanosatellite launches with forecasts are given. Digital Video Broadcasting DVB-S2 basics and some nanosatellite (so-called CubeSat) features are given. Some emergence nanosatellite researches regarding information technologies have shown, namely, MAC Protocol studies and Inter-Satellite Communication. In the Section on CubeSat teaching, we consider the US University Nanosat Program and the European Space Agency efforts, considering in more detail the OPS-SAT tools – a CubeSat developed as a training platform. As a case of the future work, one can call Satellite and 5G Integration [17].

REFERENCES

[1] Dmitry Namiot, Manfred Sneps-Sneppe. "Internet of Things and Cyber-Physical Systems at the University". *Tools and Technologies for the Development of Cyber-Physical Systems*. Springer, Berlin, Heidelberg, 2020. Chapter 11, 285-302. DOI: 10.4018/978-1-7998-1974-5.ch011

[2] Ventspils International Radio Astronomy Center https://www.virac.eu/en/about/ Retrieved: Nov, 2020

[3] LOFAR – Latvia LV614 https://www.virac.eu/en/research/technical-parameters/lofar-latvia-lv-614/ Retrieved: Nov, 2020

[4] Venta-1 https://space.skyrocket.de/doc_sdat/venta-1.htm/ Retrieved: Nov, 2020

[5] Scott C. Burleigh, Tomaso De Cola, Simone Morosi, Sara Jayousi, Ernestina Cianca, and Christian Fuchs. "From Connectivity to Advanced Internet Services: A Comprehensive Review of Small Satellites Communications and Networks". Hindavi. Wireless Communications and Mobile Computing. Volume 2019, Article ID 6243505, 17 pages. https://doi.org/10.1155/2019/6243505

[6] BRITE-Constellation. https://brite-constellation.at/ Retrieved: Nov, 2020

[7] ETSI EN 302 307 V1.3.1 (2012-11). Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband.

[8] Nasir Saeed, Ahmed Elzanaty, Heba Almorad, Hayssam Dahrouj, Tareq Y. Al-Naffouri, Mohamed-Slim Alouini, CubeSat Communications: Recent Advances and Future Challenges. IEEE Commun. Surv. Tutorials 22(3): 1839-1862 (2020). DOI: 10.36227/techrxiv.12179397.v1

[9] S. N. Mohamad Rahim, N. A. Azahari, S.A. Enche Ab Rahim and M. H. Jusoh "Development of Space-based IOT terminal for Nanosatellite UiTMSAT-1". *IOP Conf. Series: Journal of Physics: Conf. Series 1152* (2019) 012002. doi:10.1088/1742-6596/1152/1/012002

[10] Tomás Ferrer, Sandra Céspedes, and Alex Becerra, "Review and Evaluation of MAC Protocols for Satellite IoT Systems Using Nanosatellites". Sensors 2019, 19, 1947; doi:10.3390/s19081947

[11] Zizung Yoon, Walter Frese and Klaus Briess. "Design and Implementation of a Narrow-Band Intersatellite Network with Limited Onboard Resources for IoT" Sensors 2019, 19, 4212; doi:10.3390/s19194212

[12] University Nanosat Program. https://en.wikipedia.org/wiki/University_Nanosatellite_Program Retrieved: Nov, 2020

[13] Schilling K (2006) "Design of pico-satellites for education in systems engineering". IEEE Aero Electron Syst Mag 21(7): S9-S14. doi: 10.1109/MAES.2006.1684269

[14] OPS-SAT. https://en.wikipedia.org/wiki/OPS-SAT Retrieved: Nov, 2020

[15] David Evans and Mario Merri. "OPS-SAT: A ESA nanosatellite for accelerating innovation in satellite control". *SpaceOps Conference* 2014 DOI: 10.2514/6.2014-1702

[16] Danilo José Franzim Miranda, Maurício Ferreira, Fabricio Kucinskis, David McComas. "A Comparative Survey on Flight Software Frameworks for 'New Space' Nanosatellite Missions". Journal of Aerospace Technology and Management vol.11, 2019 Epub Oct 24, 2019 On-line version ISSN 2175-9146. https://doi.org/10.5028/jatm.v11.1081

[17] Giovanni Giambene, Sastri Kota, and Prashant Pillai, "Satellite -5G Integration: A Network Perspective", IEEE Network, 32(5):25-31, September 2018. DOI: 10.1109/MNET.2018.1800037