Requirements for creating an Ad-Hoc network with nanosatellites

Voraussetzungen für Aufbau von Ad-Hoc Netzen mit Nanosatelliten

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Abstract — The compact size of nanosatellites, the low cost for development and deployment and the numerous launching options make them a good fit for creating an ad-hoc network in space. Still, there are no missions that tackle all the challenges that such networks have. The currently used protocols that solve at least one of these challenges are introduced and the main characteristics of a protocol for space ad-hoc networks are presented after that. Based on that and the available deployment options the viability of such networks is shown.

Zusammenfassung — Die kompakte Größe von Nanosatelliten, die geringen Kosten für Entwicklung und Einsatz sowie die zahlreichen Startoptionen eignen sich gut für den Aufbau eines Ad-hoc-Netzwerks im Weltraum. Trotzdem gibt es noch keine Missionen, die sich mit den Herausforderungen solcher Netzwerke beschäftigen. Die derzeit verwendeten Protokolle sind diskutiert, die mindestens eine dieser Herausforderungen lösen. Danach sind die Anforderungen eines Protokolls für Weltraum-Ad-hoc-Netzwerke vorgestellt. Basierend darauf und den verfügbaren Einsatzmöglichkeiten wird die Realisierbarkeit solcher Netzwerke gezeigt.

I. Introduction

Small satellites like the nanosatellites provide a lot of promising options for space applications. Their characteristics like small size and limited power make them a good option for creating an ad-hoc network in space. Making such networks available in space has many benefits. For example it can reduce the latency in the network as well as the costs for maintaining and operating a space networks by reducing the number of required ground stations. A countless number of new applications can also be realized due to the available ISL (inter-satellite links). In the last decade many missions proved that communication between nanosatellites is possible, but none of them created a true ad-hoc network. Because these missions were focused on other tasks, they were either too small (only 2 or 3 nodes) or the protocols they used did not support creating and maintaining an ad-hoc network. We study the protocol requirements for an ad-hoc network, then we list the characteristics of such a network in space. As a next step we mention the protocols that are currently used in space for communication between satellites and what they are missing in order to be used in ad-hoc networks. Afterwards we discuss the deployment strategies of an ad-hoc network that are needed for deploying the nodes in space.

II. Ad-Hoc Protocol Requirements

An ad-hoc network is described as "a technology that enables untethered, wireless networking in environments where there is no wired or cellular infrastructure" [1]. When used with nodes that are battery powered, small in size and randomly deployed, we could define the following characteristics that describe such a network and its nodes: mobility of the nodes, multihopping, self-organization, energy conservation and scalability. In order to identify the challenges for such networks with nanosatellites we separate the ad-hoc network in two groups - a terrestrial ad-hoc network - one that is deployed on Earth, and a space ad-hoc network - one that is deployed in space and we compare them with each other.

Energy conservation is required, because the nodes are normally battery operated and have limited power reserves. This is however more important for terrestrial ad-hoc networks than for satellite networks. The reason is that in the former case, the nodes are much smaller, hundreds of grams or less [2], which leads to smaller batteries, lower transmission power, and smaller antennas, while in the latter case the nanosatellites can weight up to 10kg, thus providing much more space. Even CubeSats that consist of a couple $10cm \times 10cm \times 10cm$ units (U), each with a weight of not more than 1.33kg are significantly more relaxed space- and power-wise [3].

The energy constraints lead to another requirement - the support of multihop transmissions. The limited transmission power reduces the maximum allowed distance between nodes. This means that a message has to travel multiple hops in order to reach its destination. Multihop transmissions in satellite networks can reduce the revisit times significantly, which, dependent on the application, can lead to reduction of the latency of the network, the number of satellites and the number of ground stations that are re-

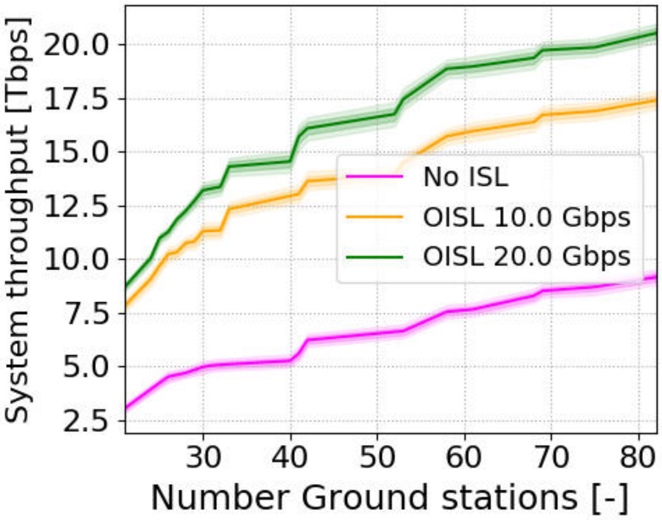

Fig. 1. OISL (optical ISL) impact on throughput for the Starlink constellation [4]

quired. On Fig. 1 the estimated impact of ISL (main requirement for multihop transmissions) on the throughput of the Starlink constellation is presented which shows that using ISL leads to a significant reduction of the required ground stations while keeping the same throughput.

Self-organization is crucial for terrestrial as well as for satellite ad-hoc networks. The satellites can be divided into two groups based on the presence of a propulsion - ones that do not have control over their position and such that can maintain the same position in space relative to the other nodes in the network. Nanosatellites very rarely have active propulsion system and for cubesats this is even more unlikely. For satellites without one, the network topology is defined based on the chosen orbits for the satellites and the deployment method. If the network is big enough so that it is not possible to launch all the nodes with just one launch vehicle, then it is very important that newly launched nodes can join an existing ad-hoc network when they are launched at later point in time. Therefore self-organization is very important for such networks from the beginning. For a small network where the nodes are sent in space with just one launching mission, the position of the nodes and their count is known and the nodes could be preconfigured with their relative position and available neighbors. This implies that no reorganizations are needed after that. However, unexpected events can occur that are not possible to predict - if one or more nodes fail on initial startup. Because of that, even for smaller networks self-organization is a requirement on launch. Another case is when a node stops functioning during the course of the mission due to faulty components, collision in space (with another satellite, meteors or other space debris) or because of drained battery. Additionally the deployment method could influence the topology due to mechanical tolerances or erroneous calculations and parameters for the separation, regardless of the dispenser used (e.g. Nanoracks CubeSat Deployer (NRCSD) from ISS or P-POD from a launching vehicle) [5]. A special case that is not part of this paper is when nodes are deployed in different orbits with different movement directions and when the nodes support cross-seam ISLs. Because the nodes enter and leave the transmission range of other nodes all the time and for short periods, a constant reorganization of the network is needed.

This last point has direct impact on another characteristic of the ad-hoc networks - the mobility of nodes. To predict how the nodes move in a terrestrial ad-hoc network is difficult most of the time and often even impossible. Therefore mechanisms in the protocols on the different layers need to be implemented to have constant update of the topology of the network, the available nodes, their link parameters like distance, interference, throughput, etc. The satellite networks have advantage in this regard, because the position and movement of the nodes can be predicted precisely enough and the changes in the topology happen rarely and can be planned [6] even with unexpected influences during the deployment.

In terrestrial ad-hoc networks it is more probable to add new nodes to the network. In satellite missions adding new nodes does not happen that often so scalability does not seem to be an important requirement. However, recently a couple of huge satellite constellation were announced and some already started being deployed in stages (e.g. Starlink from SpaceX). This proves that even though less common in the past, in the future satellite constellation could be updated more often and on stages, the number of satellites in a constellation could also be changed during the planning and the launch of the mission (Starlink have updated their constellation a couple of times [7]). This suggests that scalability is important for future satellite networks.

III. CHARACTERISTICS OF A SATELLITE AD-HOC NETWORK

Based on the discussion in the previous section a possible satellite ad-hoc network has many common characteristics with a terrestrial one, but there are also some major differences. Therefore new protocols for space ad-hoc networks should be developed that take this into consideration. Below are summarized the characteristics that such protocols should have:

- target scenario is an uncontrolled constellation mission (UC) [8]. All other types of multi-satellite missions will be covered because UC is the worst case (compared to controlled constellations and formation flying). Additionally the nodes should travel in the same orbit or in neighboring orbits in the same direction. Cross-seam ISL is very difficult to implement and maintain and for nanosatellites it is almost impossible due to requirements like fast handover algorithms, smart antennas with narrow beam, fast varying distance with severe Doppler shifts and short visibility

TABLE I. COMPARISON BETWEEN CURRENTLY USED PROTOCOLS

	mobility of nodes	multi-hop	self-organizing	energy conservation	scalability
AX.25	yes	no	no	no	no
ATM	no	NA	no	yes	NA
S-Net	yes	yes	no	yes	yes*

*up to a certain node count, due to time division on physical layer duration [9].

- use of either UHF or S-Band frequency. This is dependent on the application and performance requirements. For IoT applications UHF throughput is too low [6], but there are other application areas where UHF would be sufficient like space operation services [10]. Additionally this increased frequency reduces the size and mass of the transceivers and the size of the antenna [11], which is important for nanosatellites.

- the positions of the nodes relative to each other could be relatively stable. Nevertheless, the antenna through which a neighboring node is reachable, could change and the protocol should take this into account. A good example is described for the S-Net mission [6].

- the transmission distance should be 100km and more [6].

- the channel could be approximated with an AWGN model due to lack of shadowing and reflection [6].

IV. Protocols used in space missions

There are three protocols for which information is publicly available and that have been or are currently in use for communication between satellites with potential to support ad-hoc networks: AX.25, ATM and S-Net, because they support one or more of the characteristics of a space ad-hoc network from the previous section.

AX.25 - used in FASTRAC mission after 2010 to exchange information between 2 satellites in the same orbit. It supports both connection-oriented and connection-less operation, but there is no information which operation type was used to the best of our knowledge. Point-to-multipoint is also supported by the protocol [12], but the communication is limited to point-to-point. The goal of the mission was to establish an ISL successfully in space and to exchange information that could be used for navigation[13]. ISL was successfully established and was used to exchange GPS coordinates. AX.25 works on top of the physical layer so amateur UHF band is chosen. The satellites used the same antenna for downlink to a ground station and for ISL communication. A second antenna was used on the receiver side to receive messages via ISL. The AX.25 protocol resides in the data link layer and uses CSMA/p-persistence algorithm [12], there was no cross-layer interaction and no power control or antenna steering.

ATM (Asynchronous Transfer Mode) - although modified, it is used in the Iridium constellation since the late nineties [14] and also for the next generation of the constellation - Iridium NEXT, which launched in 2015. ATM is connection-oriented and was designed to support multiple types of data like audio, voice and data, with a later update it also supports IP over ATM. Even with the limited available information one can conclude that ATM is capable of supporting ISL. Iridium satellites have four ISLs to the neighboring satellites, 2 in the same orbit aft and forward and 2 more to satellites on different orbits [15]. Additionally, by adding telecommand and telemetry data in the data streams, the satellites can maintain permanent connectivity with each other. Power control for each transmission is also present. The algorithm for channel access is TDMA, Ka-band is used for ISL.

S-Net Proprietary protocol - used in S-Net mission to demonstrate inter-satellite communication with distributed nanosatellites and additionally to test multi-hop communication between them [5]. For that reason 4 satellites are launched. Data exchange between the ISL module and the network controller is based on Proximity-1 protocol [6], which is proposed by CCSDS (TODO short info about Proximity-1, check also in [11], on p.23 about CCSDS). The 4 satellites are launched via a dispenser one after the other in 10s interval. This method causes different orbital parameters for each node like speed and drift. Since the satellites do not have propulsion system, the distance between the nodes increases over time. The satellites use S-Band for ISL and have overall 6 antennas for maintaining the ISL connections - one on each side of the CubeSat. Since the satellites are in line formation and moving in the same orbit, each satellite communicates with the one in front of it and the one in the back. On the physical layer it uses time division, which requires synchronization among the nodes. This is performed by the ground station. Two types of communication are tested during this mission that are based on short point-to-point sessions - using scheduling (tokens) or on a competitive basis (ALOHA-like protocols). This is on physical and data link layer. On the network layer a routing protocol based on Dijkstra's algorithm is used. This mission is one of the first to demonstrate multi-hop connection between nanosatellites.

Other notable missions that provided ISL are SNAP-1 and CanX-4&5 that launched in 2000 and 2014 respectively, but the publicly available information is very limited. This is the case also with the mission called "DARPA Blackjack", which, although very secret, announced publicly its goals to demonstrate space-based mesh networks and constellation autonomy [16].

All these protocols cover one or more of the requirements of an ad-hoc network, but none of them covers all, therefore currently it is not possible to create an ad-hoc network with nanosatellites in space.

V. Deployment of nodes for a space ad-hoc network

The requirement for nodes to support ad-hoc network is not sufficient in order to create one in space. The deployment scenario of the satellites into space is very important and has to be taken into consideration. It differs significantly from deploying a network on the ground. For a typical ad-hoc network on the ground, the deployment of the nodes could be chosen either completely random (e.g. by dropping the nodes out of an airplane) or systematically (e.g. embedding in non-moving objects like buildings) [17]. Satellites cannot be deployed randomly, they are subject to regulations (e.g. radio frequency allocation) and to certifications (e.g. orbital debris mitigation compliance) [18]. Therefore nodes for satellite networks are deployed only by using a dispenser that has a limited capacity and limited options for choosing orbits and positions. Other imposed limitations are sequence, direction, velocity and time-interval. At the same time the risk of collision between the nodes during deployment or afterwards should be precisely analysed and avoided [5]. The deployment could happen via an airborne launch system, or from a dispenser from the International Space Station (ISS)[19]. If the network consists of huge number of nodes, then the mission should be divided into groups that are launched on different launch vehicles. Due to the huge costs of launching satellites, most often they are launched as a secondary payload, which limits the number of satellites per launch and the launch interval. The result of these limitation is that deployments of nodes happen in longer periods of time and that different groups of nodes get different space characteristics like altitude, drag, orbital inclinations etc. Because the nanosatellites have also a very limited life expectancy, which is typically around 1 year [20], the right planning and deployment of the mission is crucial. From an analysis of the launch opportunities from 2013, if all of them from around the world are used, a global coverage with cubesats is possible in a time frame of 6 months or less which gives at least 6 months of operation for the network [21]. In the next years this period will be significantly reduced, based on the number of launches of cubesat, which have increased 10 times from 2012 to 2017 and will increase even more in the next years [22].

VI. Conclusion

Based on the requirements of an ad-hoc network, a space ad-hoc network with nanosatellites is compared to a terrestrial one. This allows to define the specific characteristics that a node in a space ad-hoc network is required to have in order to create and maintain such a network. Until now there are no launched missions that targeted all these challenges. Three protocols are presented, that were used in successful space missions and tackled one or more of them. From the presented comparison it is apparent, that none of them can be used to create a space ad-hoc network, because there is at least one of the challenged that it does not solve. This proves the need for a new protocol for such applications. Finally the launching options are discussed and it is shown that there are enough of them that will make it possible to have all nodes deployed on time so that a space ad-hoc network can be built before the nanosatellites reach their end of life.

References

[1] P. Mohapatra and S. Krishnamurthy, *AD HOC NETWORKS: Technologies and Protocols.* Springer US, 2006.

[2] K. Sohraby, D. Minoli, and T. Znati, *Wireless Sensor Networks: Technology, Protocols, and Applications*, 08 2006.

[3] S. Lee *et al.* Cubesat design specification, rev. 13 (2015). Accessed: Sept. 10, 2020. [Online]. Available: https://www.cubesat.org/s/cds_rev13_final2.pdf

[4] I. del Portillo Barrios, B. Cameron, and E. Crawley, "A technical comparison of three low earth orbit satellite constellation systems to provide global broadband," *Acta Astronautica*, vol. 159, 03 2019.

[5] Z. Yoon, Y. Lim, S. Grau, W. Frese, and M. Garcia, "Orbit deployment and drag control strategy for formation flight while minimizing collision probability and drift," *CEAS Space Journal*, 03 2020.

[6] Z. Yoon, W. Frese, and K. Briess, "Design and implementation of a narrow-band intersatellite network with limited onboard resources for IoT," *Sensors (Basel, Switzerland)*, vol. 19, 2019.

[7] Space Exploration Holdings. Application for modification of authorizationfor the spacex ngso satellite system. Accessed: Sept. 10, 2020. [Online]. Available: https://licensing.fcc.gov/myibfs/download.do?attachment_key=2274315

[8] S. Bandyopadhyay, R. Foust, G. Subramanian, S.-J. Chung, and F. Hadaegh, "Review of formation flying and constellation missions using nanosatellites," *Journal of Spacecraft and Rockets*, vol. 53, pp. 1–12, 03 2016.

[9] K. Sidibeh and T. Vladimirova, "IEEE 802.11 optimisation techniques for inter-satellite links in leo networks," in *2006 8th International Conference Advanced Communication Technology*, vol. 2, 2006, pp. 1177–1182.

[10] Z. Yoon, W. Frese, A. Bukmaier, and K. Brieß, "System design of an S-band network of distributed nanosatellites," *CEAS Space Journal*, vol. 6, 02 2014.

[11] R. Radhakrishnan, W. Edmonson, F. Afghah, R. Rodriguez-Osorioc, F. a, and S. Burleigh, "Survey of inter-satellite communication for small satellite systems: Physical layer to network layer view," 09 2016.

[12] N. D. Beech W. and T. J., "AX.25 link access protocol for amateur packet radio," 1997, accessed: Sept. 10, 2020. [Online]. Available: http://www.tapr.org/pdf/AX25.2.2.pdf

[13] S. Muñoz Toro, J. Greenbaum, G. Lightsey, T. Campbell, S. Stewart, and G. Holt, "The fastrac mission: Operations summary and preliminary experiment results," 08 2011.

[14] K. Kusza and M. Paluszek, "Intersatellite links: Lower layer protocols for autonomous constellations," p. 13, 11 2000.

[15] Iridium Constellation. Iridium next engineering statement. Accessed: Sept. 10, 2020. [Online]. Available: http://licensing.fcc.gov/myibfs/download.do?attachment_key=1031348

[16] DARPA. Broad agency announcement blackjack pit boss. Accessed: Sept. 10, 2020. [Online]. Available: https://www.darpa.mil/attachments/HR001119S0012-Amendment-02.pdf

[17] A. Kumar, D. Manjunath, and J. Kuri, "Chapter 8 - multiple access: Wireless networks," in *Communication Networking*, ser. The Morgan Kaufmann Series in Networking, A. Kumar, D. Manjunath, and J. Kuri, Eds. San Francisco: Morgan Kaufmann, 2004, pp. 435 – 531.

[18] J. Chin *et al.* Cubesat 101 basic concepts and processes for first-time cubesat developers. Accessed: Sept. 10, 2020. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/nasa_csli_cubesat_101_508.pdf

[19] N. Crisp, K. Smith, and P. Hollingsworth, "Launch and deployment of distributed small satellite systems," *Acta Astronautica*, vol. 29, 04 2015.

[20] J. Bouwmeester, M. Langer, and E. Gill, "Survey on the implementation and reliability of cubesat electrical bus interfaces," *CEAS Space Journal*, vol. 9, pp. 163–173, 2017.

[21] A. Marinan, A. Nicholas, and K. Cahoy, "Ad hoc cubesat constellations: Secondary launch coverage and distribution," in *2013 IEEE Aerospace Conference*, 2013, pp. 1–15.

[22] E. Kulu. Nanosatellite launches with forecasts. Accessed: Sept. 10, 2020. [Online]. Available: https://www.nanosats.eu/