Interference-Free Store-and-Forward Communication in Low Earth Orbit Satellite Systems

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***Abstract*—Multi-satellite systems in low Earth orbits based on nanosatellites can be used for Earth observation and global store-and-forward communication. The intersatellite links in these systems need to be coordinated in a way that avoids interference, and optimises throughput, delays and energy consumption. Existing contact plan design approaches do not prevent packet loss due to interference of nodes, and the use of additional Medium Access Control (MAC) schemes such as Carrier-sense multiple access with collision avoidance (CSMA/CA) is inefficient in networks with high propagation time and dynamic topology. In this paper, a contact plan based design approach is presented that solves the MAC problem by predicting additive interference and scheduling interference-free inter-satellite links in advance. The presented approach is part of a Delay Tolerant Network (DTN) routing protocol for space-terrestrial networks. An improvement of the algorithm is also presented to reduce computational effort. Performance was evaluated for different orbit configurations using a satellite network simulation framework based on the Objective Modular Network Testbed in C++ (OMNeT++).**

***Keywords*–Satellite Communication; Delay Tolerant Network; Medium Access Control; Satellite Formations.**

I. Introduction

The most promising application scenarios for multi-satellite systems based on nanosatellites are Earth Observation (EO) and Machine-to-Machine (M2M) communication. Nanosatellite based systems for Earth observation are already in use, such as the constellation of Planet [1] with its Dove satellites. In the future, satellite formations will be launched that capture 3D information, such as CloudCT [2], a formation of ten satellites build by the Center for Telematics (ZfT) Würzburg. In this mission, 3D information of clouds will be acquired by a satellite formation flying in a dense orbit configuration. For satellite based communication systems, spatially distributed orbit configurations are used due to their high spatial and temporal coverage of the Earth's surface. Accordingly, a globally distributed satellite system and a dense satellite formation have been used for evaluation of the presented approach.

Both M2M and EO satellite systems could take advantage of the development of efficient communication protocols by increasing throughput, faster availability of data and more efficient use of resources. The goal of the presented approach is to take advantage of the predictability of the dynamic topology of satellite networks for the design of routing algorithms. In the next section, the basic principle of the presented approach will be described, before, in Section III, a contact plan design approach, called Interference-Free Contact Plan Design (IFCPD) is presented. The performance of this approach is evaluated in Section IV, followed by a conclusion in Section V.

II. DTN Routing

Communication in low Earth orbit satellite systems can benefit from Delay/Disruption Tolerant Network (DTN) protocols to cope with intermittent and unreliable links. Routing in such a network can be difficult, but routing algorithms can make use of the knowledge about a system. The motion of satellites is highly predictable. Instead of a topology discovery mechanism, contact plan based routing utilises predefined contact plans of the network. Therefore nodes can make routing decisions based on future contacts within the network. So far no Multiple Access Control (MAC) scheme is available that makes use of the available contact plans. Therefore standard MAC schemes need to be used to prevent packet loss, such as CSMA/CA, which is inefficient in Low Earth Orbit (LEO) networks as shown in [3]. As a basis for the presented approach, a simplified general perturbations (SGP4) propagator [4] was integrated into an OMNeT++ based simulation framework to predict satellite positions. By propagating satellite positions, the network topology and the node distances can be calculated with sufficient accuracy for days in advance. The predicted topology is stored in a contact plan that consists of multiple contact entries. A contact is defined by its start time, end time, source node, sink node and a data rate. The contact plan is converted to a space time graph for routing purposes. The vertices of a space time graph are network nodes. Edges are either the contacts from the contact plan or edges between copies of the same network nodes representing storage of data on these nodes. In this graph, the shortest routes for all pairs of nodes are computed and stored in routing tables. For more details on this approach please refer to [3]. The presented contact plan design approach is compatible with Contact Graph Routing (CGR) [5], a contact plan based routing approach for the Bundle Protocol [6].

III. Interference-Free Contact Plan Design

The satellites are assumed to be equipped with isotropic antennas and typical Ultra High Frequency (UHF) transceivers with a transmit power of $0.5W$. Transmissions are assumed to be successful if the received signal-to-interference-plus-noise ratio (SINR) is at least $5.82dB$.

To create a contact plan for a specific orbit configuration, a check for all pairs of nodes is performed, on whether these pairs are able to communicate with each other. For each of these contacts, potential interfering nodes are identified by iterating over all transmitters that exist in the simulation scenario. In a system with n nodes, there are $n-2$ nodes that could generally cause interference on a link, so $n-2$ interference checks have to be performed to identify which nodes would cause interference on a link at a specific point in time. Furthermore constructive interference of signals produced by two or more nodes could cause packet loss, which is also called additive interference. To identify all sets of interfering links, $2^{(n-2)}-1$ checks need to be performed in the worst case. In scenarios with a high number of network nodes and long prediction intervals additive interference checks require a very high computational effort. However, the number of checks can be reduced by more than half for each node that can be excluded from the list of potential interfering nodes. To improve performance, all nodes are stored in a spatial data structure (k-d tree) so that a radius search can be applied with the radius equal to the line-of-sight distance. Thereby all nodes that are not separated by Earth can be picked for interference evaluations. The radius search is also applied during contact plan creation by using the communication range as radius. Using a contact and an interference plan, maximal sets of non-interfering contacts can be calculated. These independent sets can be determined by the following algorithm:

Initialization: Create a bin for each contact within a contact plan time interval and a list of the succeeding contacts.

1) For all bins generated in the previous iteration, iterate through the contacts of the corresponding list, create a copy of the bin, add the selected contact and a list of the succeeding contacts.
2) For all bins generated in the previous step, check if the last contact in the bin interferes with any subset of the contacts in the bin. Delete the corresponding bin if interference was detected.
3) If all lists are empty stop here, otherwise continue with step 1.

Finally, check for redundant bins and remove them.

IV. EVALUATION

Evaluations have been performed in two mission scenarios and compared by runtime and packet delivery ratios.

A. Runtime comparison

To evaluate the performance improvement of the radius search, a 40 minute contact and interference plan with additive interference checks for a $45° : 18 : 6 : 0$ walker constellation at an altitude of 698km has been created on a standard PC. The calculations have been performed for a period of 40 minutes. The runtime with radius search was 0.56s, compared to 342.86s without radius search. If just a contact plan was generated for one day the runtime could be reduced from 4.47s to 1.16s. This proves that using a spatial data structure with an efficient radius search increases the performance of contact and interference plan calculations significantly. This improvement is mainly important to be able to consider additive interference in larger satellite systems.

B. Packet loss

To evaluate the packet delivery ratio of the IFCPD algorithm, a 10 satellite string-of-pearls formation comparable to the CloudCT mission was analysed. The simulated altitude is 600km and the node separation is 100km. In the simulated scenario, each satellite tries to transmit data to its successor during a 10,000s simulation period. The satellites transmit one packet every 10s simultaneously to focus on the analysis of situations where packet loss would occur due to interference.

TABLE I. PACKET DELIVERY RATIOS OF THE EVALUATED ALGORITHMS

Algorithm	Packet Delivery Ratio
FCP	0%
IACPD	97.6%
IFCPD	100%

The IFCPD approach was compared to the previous version, called Interference-Aware Contact Plan Design (IACPD), presented in [3] and to the basic CGR [5] approach with a Full Contact Plan (FCP) that includes all possible communication opportunities. IACPD does only consider interference caused by single satellites, while the use of a FCP does not avoid interference at all.

Table I shows the summarised evaluation results. In case a full contact plan is used, 100% of the transmitted packets are lost due to interference. IFCPD is able to deliver all packets, while IACPD produces a packet loss of 2.4%.

V. CONCLUSION

The presented contact plan design approach IFCPD was able to prevent packet loss in simulated wireless satellite networks and seems to be a suitable and efficient approach for LEO networks. The presented improvement of IFCPD based on radius search significantly reduces the computational effort. Nevertheless, performance of the algorithm for the calculation of independent sets has to be improved to enable calculation of plans for scenarios with a higher number of nodes and longer prediction intervals. Furthermore, since system models are used to predict future states of a system, the performance of the presented approach will depend on the quality of these models. Therefore, we will further investigate the robustness of the approach in case of model errors.

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REFERENCES

[1] C. Boshuizen, J. Mason, P. Klupar, and S. Spanhake, “Results from the Planet Labs Flock Constellation,” in *28th Annual AIAA/USUConference on Small Satellites*, 2014.

[2] ERC Synergy Grant ”CloudCT” awarded. Last accessed 18 March 2019. [Online]. Available: http://www7.informatik.uni-wuerzburg.de/news/single-news/news/erc-synergy-grant-cloudct-awarded

[3] T. Thiel, A. Freimann, and K. Schilling, “Contact plan based routing in distributed nanosatellite systems,” in *69th International Astronautical Congress (IAC)*, 2018.

[4] D. A. Vallado and P. Crawford, “SGP4 orbit determination,” in *Proceedings of AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, 2008, pp. 18–21.

[5] G. Araniti et al., “Contact graph routing in DTN space networks: overview, enhancements and performance,” *Communications Magazine, IEEE*, vol. 53, no. 3, pp. 38–46, 2015.

[6] S. Burleigh and K. Scott. (2007) Bundle protocol specification. Last accessed 10 December 2018. [Online]. Available: http://tools.ietf.org/html/rfc5050