Reliability and Bandwidth Advantages of LEO Satellite Cluster Networking in Space-to-Earth Laser Communication

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Abstract *To solve the problem of unreliable space-to-earth laser communication caused by rapidly changing atmospheric conditions, a novel satellite-cluster-based channel-adaptive laser communication architecture was proposed. Simulation and emulation results show that the proposed architecture can significantly improve communication availability and bandwidth in medium cloud coverage scenarios.*

Introduction

As mega low earth orbit (LEO) satellite networks are widely used in communication, remote sensing and other Internet services [1]. extremely large amounts of data generated or forwarded on satellites need to be transmitted to the ground in real time [2], resulting in the demand for space-to-earth (S2E) communication rates increasing. Compared with radio frequency (RF) communication, laser communication can provide much higher data rate of up to 100Gbps[3]. However, the quality of the S2E laser communication executed by a single satellite can fluctuate severely due to uneven cloud coverage at the optical ground stations (OGS), resulting in frequent and prolonged unreliable communication. This hinders the practical application of laser link in S2E communication. Therefore, there is an urgent need for a method that can cope with cloud attenuation and achieve reliable S2E laser communication.

In this paper, we propose a novel channel-adaptive S2E laser communication (CA-S2E-LC) architecture based on satellite cluster optical networking (SCON). As shown in Fig. 1, a reconfigurable and scalable satellite cluster with a diameter up to 100km can be used as a virtual satellite to replace a single monolithic satellite in a mega LEO satellite optical network [4-6]. It is obvious but underappreciated that the S2E laser links established by every member satellite can form spatial diversity. Based on this characteristic, the proposed CA-S2E-LC architecture can adaptively select the link that is not affected by clouds to achieve reliable S2E laser communication. We verify the reliability and bandwidth advantages of the proposed architecture through simulations and experiments.

Proposed architecture based on SCON

The system block diagram of the CA-S2E-LC architecture is shown in Fig. 2. In this architecture, each member satellite periodically initiates link quality indication (LQI) test by polling, collects the LQI calculated by the LQI Analyser configured in OGSs, and establishes intra-cluster and S2E lightpaths according to certain strategies.

Fig. 3 illustrates the message flow of the CA-

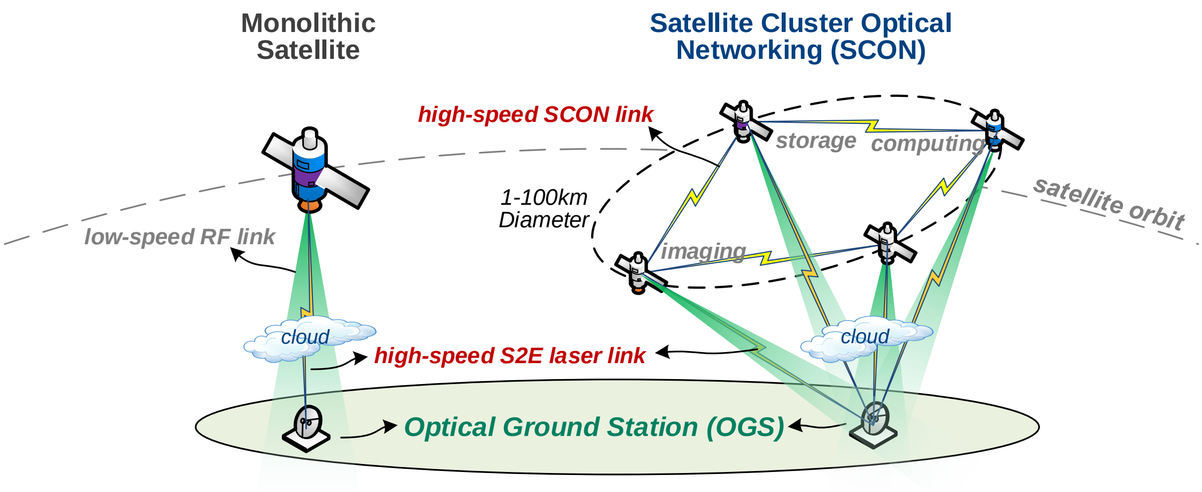

Fig. 1: Comparison of space-to-earth communication architectures: single monolithic satellite vs. satellite cluster.

S2E-LC architecture. When the satellite cluster and the OGS are visible to each other, each member satellite equipped with the S2E laser communication payload successively and periodically tests the link quality. The OGS analyses and broadcasts the LQI in real time to the satellite cluster via tracking, telemetry and control (TT&C) payloads. All member satellites' LQIs can be used as the basis for implementing S2E laser communication strategy. For example, this work demonstrates a single direct to earth (DTE) satellite selection strategy: One DTE satellite with the best LQI is chosen to establish the S2E laser link.

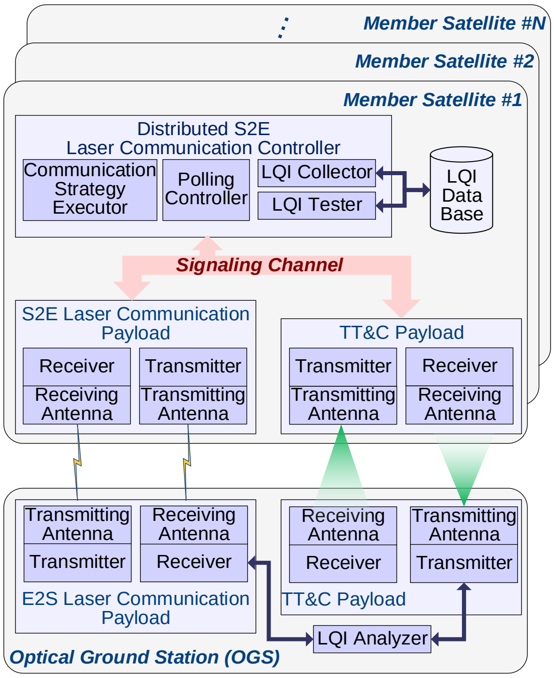

Fig. 2: Schematic system block diagram.

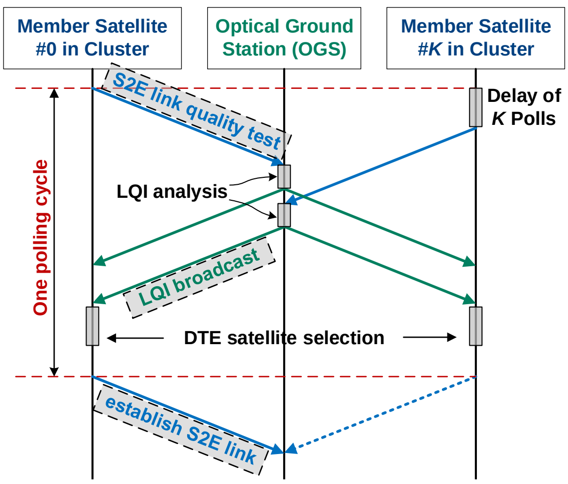

Fig. 3: Message flow of CA-S2E-LC.

Simulation setup and results

To verify the performance of the proposed architecture, we modelled the spatio-temporal distribution and power budget of the S2E laser links, as well as the relative motion of satellite cluster.

Referring to ITU-R P recommendations [7-12], the spatio-temporal distribution model takes into account free-space attenuation and atmospheric attenuation (including gaseous, cloud and scintillation attenuation) under cloudy weather (Eq. (1)). It should be emphasized that the fractal Brownian motion model is used to simulate the uneven cloud layer. The specific parameters of the model are shown in Tab. 1.

$$\mathrm{L} = L_{freespace} + L_{gaseous} + L_{cloud} + L_{scintillation} \quad (1)$$

Tab. 1: Parameters of the S2E laser link spatio-temporal distribution model.

Parameter	value unit
Vertical cumulative gaseous attenuation in clear weather	0.56 dB
The mean/variance of the total columnar content of cloud liquid water	0.101/0.0364 kg/m^2
Cloud height	6 km
Cloud cover	70%
OGS surface temperature	273.15 K
Root-mean-square wind speed	21 m/s
The nominal value of turbulence height at ground level	1.7e-4 m$^{-2/3}$

The power budget model calculates OGS received power and Shannon capacity in real-time according to the parameters of the satellite laser/RF communication payloads, the OGS receivers and the S2E laser/RF communication channel, which are shown in Tab. 2.

Tab. 2: Parameters of the power budget model.

Parameter	Value unit	
Band	RF (Ku)	Optical
Wavelength	2.22 cm	1549 nm
Equivalent isotopically radiated power	66.7 dBm	98.8 dBm
Receiving antenna gain	37.7 dBi	129.7 dBi
Bandwidth	0.25 GHz	10 GHz
Equivalent noise power	3.16 e^{-11} W	1e^{-7} W

Tab. 3: Parameters of satellite cluster relative motion model.

Reference satellite	Semi-major axis	6914 km
	Eccentricity	0.01
	Inclination	60 deg
	Depression of perigee	60 deg
	Right ascension of the ascending node	30 deg
	Mean anomaly	120 deg
Satellite cluster	Configuration	Circle
	Radius of circle	15/25 km
	Number of satellites	13
OGS	Altitude	1.85 m

Based on the relative motion equation of satellites, the satellite cluster relative motion model calculates a group of Kepler orbits for member satellites to keep the relative position of member

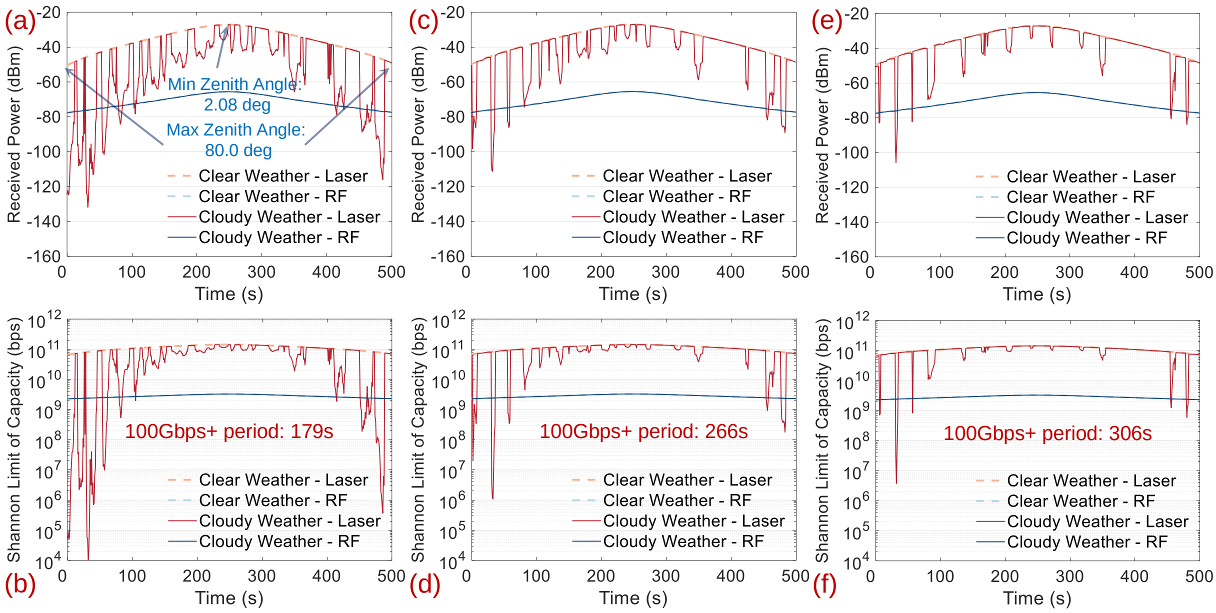

Fig. 4: The received power and the Shannon limit of capacity in (a), (b) monolithic satellite, (c),(d) satellite cluster with 15 km radius and (e),(f) satellite cluster with 25 km radius.

satellites stable and distributed on an ellipse parallel to the ground. The parameters of the model are shown in Tab. 3.

Fig. 4 compares the performance of monolithic satellite and CA-S2E-LC. The single DTE satellite selection strategy is used to establish lightpaths. It can be seen that for the monolithic satellite, cloud cover can cause severe decrease on link availability. In comparison, CA-S2E-LC significantly improves the received power and capacity. Especially for the 25-km radius cluster, the 100Gbps+ communication period can be improved by 70.95% in cloudy weather.

Emulation setup and results

An multi-node emulation platform is established to verify the message flow of CA-S2E-LC (Fig. 5). The distributed satellite cluster/OGS emulators periodically send time and satellite number, coordinates and other information to the channel estimator (Fig.6), which calculates channel attenuation using pre-set atmospheric data. These attenuation values are integrated according to the polling cycle and sent to a arbitrary waveform generator (AWG) to control the fast variable optical attenuator (VOA) to complete the simulation of S2E channel attenuation. The polling cycle time and the duration of each poll are set to 1s and 1ms, respectively. Fig. 7 shows the received power of each channel from the DSO and the DTE satellite selection results over five polling cycles.

Conclusions

In this paper, a novel channel-adaptive S2E laser communication architecture based on SCON is proposed. The reliable high-speed S2E laser communication can be achieved by constructing the spatial diversity link group and adaptively selecting the optimal links. Future research will focus on the optimal configuration and routing strategy of satellite clusters to adapt to different weather conditions and meet different service quality requirements.

Fig. 5: Emulation setup.

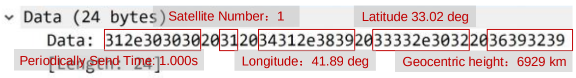

Fig. 6: Information sent from a satellite emulator to the channel estimator.

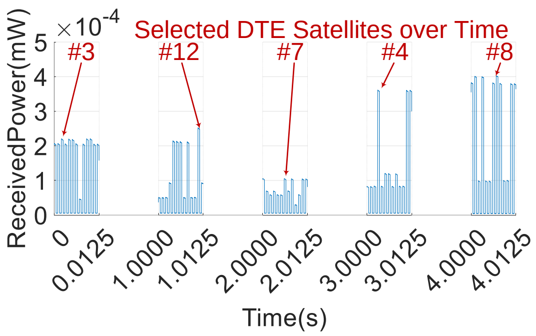

Fig. 7: Received power at OGS.

Acknowledgements

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