Optical Satellite Systems for ns-3

Michael Di Perna

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1 Project Overview

The Optical Satellite Systems project looks to provide a model in ns-3 for optical communication between satellites and groundstations, and inter-satellite communication. The project will work on constructing the lower level components of the communication system. These components include the channel model, antenna model (laser and optical receiver), and the physical layer. The European Data Relay System (EDRS) is the primary use case that is helping guide design decisions in this project.

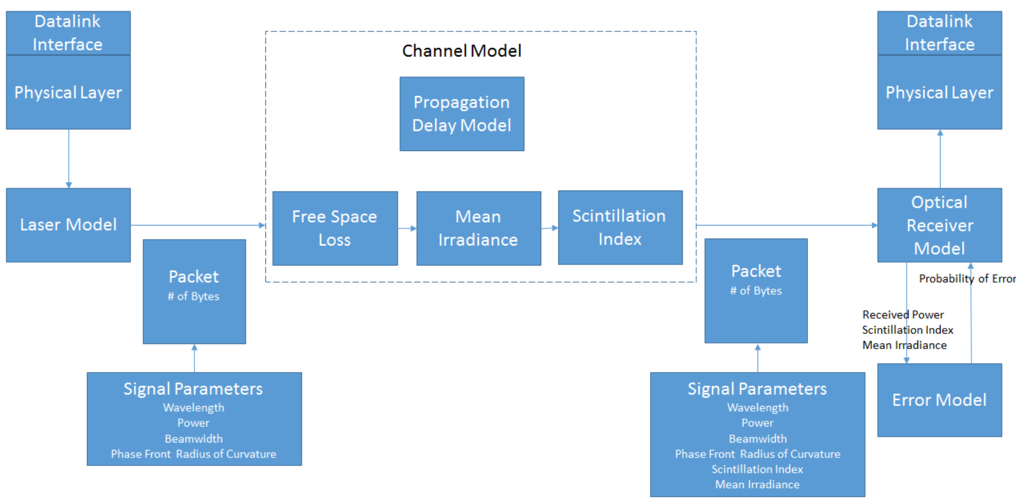

Figure 1: OSS Block Diagram

2 ns-3 Simulator

ns-3 is a discrete-event, packet level simulator. The unit of modeling granularity is the packet; on a channel model, it is packets and not bits or symbols that are scheduled to be received after passing through models of propagation loss and fading. It is a full-stack simulator, enabling people to run higher layer protocols and even virtual machines on top of wireless abstractions. In this regard, ns-3 is more like the commercial OPNET simulator than like either link simulators like MATLAB or satellite systems simulators like STK.

As a result, we seek some guidance on what is the proper level of abstraction of optical satellite link for a packet-level simulator. **What are the key first-order physical layer performance effects that we must capture in the model? Are there any other packet-level simulators for optical satellite systems which we could reference? Are there any communities/mailing lists that we could ask modeling questions to?**

3 Channel Model

The channel model is currently aiming to provide an accurate model of the geo-synchronous to optical ground station channel. The model provides the irradiance (Watts/meter) at the receiver, which is described by a log-normal distribution [1]. The distribution of the irradiance at the receiver, $p_I(I)$,is a function of the scintillation index σ_I^2 and the mean irradiance $\langle I(\mathbf{r}, L)\rangle$:

$$p_I(I) = \frac{1}{I\sigma_I(\mathbf{r}, L)\sqrt(2\pi)} exp\Bigg(- \frac{\Big[ln\big(\frac{I}{\langle I(\mathbf{r},L)\rangle}\big) + \frac{1}{2}\sigma_I^2(\mathbf{r}, L)\Big]^2}{2\sigma_I^2(\mathbf{r}, L)}\Bigg) \tag{1}$$

where $\mathbf{r}$ is the transverse observation point. The mean irradiance and can be expressed as follows:

$$\langle I(\mathbf{r}, L)\rangle = \frac{W_0^2}{W_{LT}^2} exp\bigg(- \frac{2r^2}{W_{LT}^2}\bigg) \tag{2}$$

where W_0^2 is the beam radius at the transmitter, W_{LT}^2 is the effective spot size of the beam in the presence of atmospheric turbulence, and r is the radial distance from the center of the beam. The scintillation index can be simplified in the downlink case, due to the beam effectively appearing as an unbounded plane wave once it enters the atmosphere. We are currently not considering the uplink case. The scintillation index used for the downlink model is:

$$\sigma_I^2(r, L) = 2.25k^{7/6} \sec^{11/6}(\zeta) \int_{H_{GS}}^{H} C_n^2(h)[h - h_{GS}]^{5/6}\, dh \tag{3}$$

where $k = 2\pi/\lambda$ and λ is the wavelength of the optical beam, H is the altitude of the transmitter, ζ is the elevation angle, H_{GS} is the altitude of the ground station, and $C_n^2(h)$ is the index of refraction of the atmosphere as a function of altitude. The index of refraction can be described by a modified version of the

Hufnagel-Valley model [2]:

$$\begin{aligned}C_n^2(h) =& Ae^{-H_{GS}/700}e^{-(h-H_{GS})/100} \\ &+ 5.94 \cdot 10^{-53}\frac{v^2}{27^2}h^{10}e^{-h/1000} \\ &+ 2.7 \cdot 10^{-16}e^{-h/1500}\end{aligned} \tag{4}$$

where A is the refractive index structure parameter at ground level and v is the root-mean-square wind speed. We will be considering a constant delay for the link. Mie scattering could also be modeled, which provides a model for scattering due to small water particles. The attenuation due to Mie scattering is

$$A_s = \frac{4.3429\tau'}{\sin\theta} \tag{5}$$

where θ is the elevation angle τ' is the extinction ratio. The extinction ratio is a polynomial which has coefficients dependent on the wavelength of the optical beam. **Does this model seem reasonable? Are there any other effects we could model?**

4 Laser and Optical Receiver Model

The model of the laser includes the beamwidth (the distance from the center of the beam to the point at which the amplitude is $1/e$ of the center), the phase front radius of curvature (characterizes the shape of the beam: divergent, convergent, or collimated), and the transmit power.

The model of the optical receiver will include the aperture size (for computing received power) and the receiver gain. The optical receiver will obtain the irradiance from the channel model and the compute the received power. It will then use the provided error model to determine if the received packet has been corrupted or not. For the transmitter and receiver paramters, we were considering using values from published experimental results (i.e. the Kirari and ARTEMIS link). **Can you recommend any sources for providing realistic rx/tx parameters such as beamwidth, aperture size, etc. ?**

The error model may include the bit error rate (BER) which will be dependent on the calculated signal to noise ratio (SNR). We are assuming on-off keying (OOK) as the modulation scheme. The SNR will be the average value for the channel. We should be able to calculate the mean fade duration, which provides a mean time for which the irradiance at the receiver drops below a given threshold. A threshold would be chosen that would represent a "bad" state for the channel in which communication would not be possible. The mean fade time would provide the duration that the link is unavailable. We have been advised that the greenwood time constant provides a time scale for fade durations and is expressed as follows [1]:

$$\tau_0 = \left(2.91k^2\int_0^L C_n^2V^{5/3}(z)dz\right)^{-3/5} \tag{6}$$

where $V(z)$ is the transverse wind speed. **Would combining the mean fade time and the average BER be an appropriate model for the link? Are there other error models which we should investigate? Besides OOK, are there any other modulation or coding schemes we should consider?**

5 Physical Layer Model

We would like to model this layer according to the "Optical Communications Physical Layer" standard currently in development by the CCSDS. The Proximity-1 Space Link Protocol may be appropriate to consider until the Optical Communications Physical Layer protocol is publicly available. **Would tracking errors be of interest to users of our model? How would this be modeled?**

6 References

[1] "Laser Beam Propagation through Random Media". Larry C. Andrews and Ronald L. Philips.
[2] "Digital Modulation and Coding for Satellite Optical Feeder Links". S. Dimitrov et al. 2014 7th Advanced Satellite Multimedia Systems Conference and the 13th Signal Processing for Space Communications Workshop (ASMS/SPSC).