# Link-Level Performance Analysis of DVB Standards in Ultra-Dense LEO Satellite-Terrestrial Networks

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***Abstract*—Ultra-dense low earth orbit (LEO) satellite terrestrial networks (ULSNs) are considered as a crucial component of future six generation (6G) networks, offering ubiquitous and massive services for various applications. However, for the development of advanced physical layer technologies for ULSNs, a comprehensive link-level simulation tool that integrates up-to-date satellite communication protocols becomes paramount and is urgently needed. In this paper, we develop a versatile simulator for the link-level performance analysis of ULSNs under the prevalent digital video broadcasting (DVB) standards. We first establish a complete satellite-terrestrial microwave channel model, taking practical factors such as rain attenuation, cloud attenuation, and Doppler frequency shift into consideration. Subsequently, the whole physical layer modules tailored for satellite-terrestrial microwave communication are implemented, including diverse physical layer modulation and coding schemes (MCSs). Furthermore, we realize adaptive coding and modulation (ACM) for adaptive channel performance simulation. Finally, comparative performance analysis using the established channel model is conducted to demonstrate the effectiveness of different MCSs of DVB standards. The complete link-level performance analysis based on our self-developed simulator can advance the field of satellite-terrestrial microwave communication and provide valuable insights for further exploration of ULSNs.**

***Index Terms*—Ultra-dense LEO satellite-terrestrial networks, link-level simulation, DVB protocol, physical layer, modulation and coding scheme.**

## I. Introduction

The ubiquitous and massive demand for communications in future six generation (6G) era will pose challenges on traditional terrestrial networks which are unable to provide sufficient communication coverage in remote areas and hot spots [1]. In recent years, with the development of ultra-dense low earth orbit (LEO) satellite constellations, such as Starlink and OneWeb, full coverage can be realized without geographic constraints [2]. In this context, ultra-dense LEO satellite-terrestrial networks (ULSNs) have become an important means of compensating for the shortcomings of traditional terrestrial networks. In the realm of ULSNs, SpaceX has introduced the innovative capability of "Starlink Direct to Cell" service that plans to offer cellular connectivity to terrestrial user equipment via LEO satellite and employs the Digital Video Broadcasting (DVB) physical layer standard [3]. Consequently, the significance of conducting rigorous link-level simulation at the physical layer becomes paramount for performance evaluation of transceiver architectures and novel techniques in ULSNs.

For link-level simulation in ULSNs, the communication channel between LEO satellite and the terrestrial user equipment is the key in the transmission path, which will significantly influence the overall performance of the communication system [4]. Moreover, the accuracy of predicting and evaluating the physical layer performance of modulation and coding schemes (MCSs) in ULSNs is significantly impacted by the selection and precision of the channel model. Therefore, the study of channel characteristics and modeling poses significant challenges and holds paramount importance for the link-level simulation in ULSNs. Liu *et al*. designed a system-level simulator supporting basic representatives of networking nodes, structures and protocol stacks in ULSNs [5]. To assess the performance of the DVB standards in ULSNs, Kassing *et al*. designed the Satellite Network Simulator 3 (SNS3) leveraging an extensive array of pre-existing ns-3 models and functionalities. It incorporates the medium access control (MAC) layer of DVB-S2/S2X and DVB-RCS2 protocols for packet-level data transmission [6]. However, previous researches [5]–[8] related to simulations for LEO satellites mainly focus on system-level simulation of MAC layer which are packet-level and do not involve link-level simulation of the physical layer under precise modeling of LEO satellite-terrestrial channel.

Currently, there is a lack of link-level simulations that provide physical layer functionality of DVB standards for ULSNs. In this paper, we design a link-level simulator of ULSNs and develop a mathematical model for LEO satellite-terrestrial channel. Subsequently, we incorporate various physical layer MCSs into our framework. Three main contributions of this paper in the light of existing works are summerized as follows:

- We present a comprehensive model for LEO satellite-terrestrial channel taking into crucial factors, such as rain attenuation, cloud attenuation, and Doppler shift.
- We delve into the implementation of link-level simulator for the physical layer of ULSNs under DVB standards supporting various MCSs and extend our efforts to the realization of adaptive coding and modulation (ACM).
- Comparative performance analyses of different MCSs are conducted based on the established channel models. Simulation results show that DVB-RCS2 has better bit

error rate (BER) performance compared to DVB-S2/S2X.

The rest of this paper is organized as follows. In Section II, channel model for ULSNs are introduced. Section III presents the module design of the link-level simulation under DVB standards in ULSNs. The simulation results are presented in Section IV. And Section V is the conclusion.

## II. Channel Model for Satellite-Terrestrial Networks

In this section, we establish the channel model for communications between LEO satellites and terrestrial user equipments. Crucial channel factors including basic path loss, gas attenuation, rain and cloud attenuation, scient attenuation and Doppler shift are taken into account.

### A. Basic Path Loss

The basic path loss $PL_b$ between LEO satellite and terrestrial user equipment is expressed as

$$PL_b = P_{FS}\left(d, F_c\right) + P_{SF} + P_{CL}\left(\alpha, F_c\right), \tag{1}$$

where $d$ is the distance between user equipment and LEO satellite, $F_c$ is the carrier frequency, $\alpha$ is the elevation angle of LEO satellite, $P_{FS}$ denotes the free space loss, $P_{SF}$ denotes the shadow fading loss (SF) and $P_{CL}$ is the clutter loss (CL). The free space loss is

$$P_{FS}\left(d, F_c\right) = 32.45 + 20\log_{10}\left(F_c\right) + 20\log_{10}(d). \tag{2}$$

According to the geometry model for LEO satellite and terrestrial user equipment shown in Fig. 1, the distance between LEO satellite and user equipment can be expressed as

$$d = \sqrt{R_e^2 \sin^2\alpha + h^2 + 2hR_e} - R_e \sin\alpha, \tag{3}$$

where $R_e$ is the earth radius, $h$ is the LEO satellite orbit height.

SF $P_{SF}$ obeys a lognormal distribution with a standard deviation of $\sigma_{SF}^2$ depending on the scenario. CL is the attenuation of signal power caused by surrounding buildings and ground objects, which depends on the elevation angle $\alpha$, the carrier frequency $F_c$, and the scenario including uburban and rural, dense urban and urbans. The values of SF and CL can be found in [9].

### B. Attenuation

Ultra hight frequency (UHF) bands (3-30 GHz) and extremely high frequency (EHF) bands (30-300 GHz) are commonly used for future LEO satellite-terrestrial communications in ULSNs. In this subsection, we model channel fading in the UHF and EHF bands based on ITU standards.

*1) Gas Attenuation:* Gas attenuation is caused by the absorption and scattering of atmospheric gases, and is usually negligible at frequencies below 10 GHz. Atmospheric attenuation depends mainly on the carrier frequency, elevation angle, altitude and absolute humidity of water vapor. According to ITU-R P.676-6 [10], gas attenuation can be represented as

$$PL_G\left(\alpha, F_c\right) = \frac{A_{\text{zenith}}\left(F_c\right)}{\sin(\alpha)}. \tag{4}$$

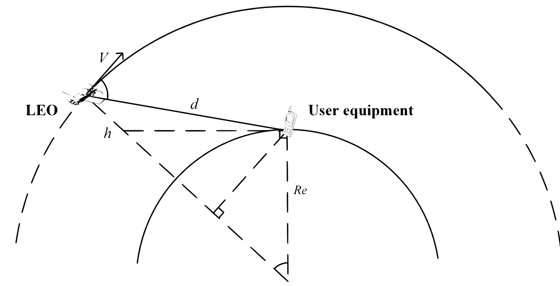


Fig. 1. The geometry model for LEO satellite and terrestrial user equipment.

*2) Rain Attenuation:* Rain attenuation is mainly caused by rainfall, and prediction methods for long-term rain attenuation statistics are considered for a given latitude and longitude of the terrestrial user equipment in order to study the characteristics of rain attenuation variations which can be expressed as

$$PL_R = k(R_{0.01})^{\beta} L_E, \tag{5}$$

where $L_E$ denotes the effective length of rainfall, $R_{0.01}$ denotes average annual rainfall with a probability of more than $0.01\%$, $k$ and $\beta$ are both constant.

*3) Cloud Attenuation:* For modeling cloud attenuation refer to the ITU-R P.840 standard [11], the specific attenuation within the cloud or fog through the Rayleigh approximation can be written as

$$PL_C = K_l(F_c, T) M L_c, \tag{6}$$

where $M$ is the density of liquid water in clouds or fog, $L_c$ is the path length of data transmit in cloud, $T$ is the temperature of liquid water in clouds or fog and $K_l$ is specific attenuation coefficient of liquid water in clouds decided by $F_c$ and $T$ which can be calculated according to double-Debye model.

*4) Scintillation:* For frequencies greater than 6 GHz, tropospheric scintillation losses are considered, caused mainly by transient fluctuations in signal amplitude and phase due to atmospheric turbulence, which leads to degradation of the received signal quality

$$PL_S = a(p)\sigma_{ref} F_c^{7/12} \frac{g(x)}{(\sin\alpha)^{1.2}}, \tag{7}$$

where $\sigma_{ref} = 3.6\times10^{-3} + 10^{-4}\times N_{wet}$ and $N_{wet}$ is the wet term of the radio refractivity [9].

$$g(x) = \sqrt{3.86\left(x^2+1\right)^{\frac{11}{12}} \sin\left[\frac{11}{6}\arctan\frac{1}{x}\right] - 7.08x^{\frac{5}{6}}}, \tag{8}$$

where $x = 0.61D^2F_c/2000\left(\sqrt{\sin^2\theta + 2.35\times10^{-4}} + \sin\theta\right)$.

### C. Doppler Shift

The Doppler shift depends on the speed of the LEO satellite, the speed of the user equipment and the carrier frequency. Since the speed of the ground equipment is negligible relative to that of the LEO satellite [12], only the operating speed and carrier frequency of the LEO satellite are taken into account. The Doppler shift is expressed as

$$F_d = \frac{F_c}{c} V \cos\theta, \tag{9}$$

where $F_c$ is carrier frequency, $V$ is the speed of LEO satellite, $\theta$ is the angle between the signal transmission direction vector and the velocity vector. As shown in Fig. 1, $\theta$ varies with the motion of the satellite and the Doppler shift is deduced as

$$F_d = \frac{F_c}{c} V \frac{\sin u}{\sqrt{1 + \left(\frac{R_e+h}{R_e}\right)^2 - 2\frac{R_e+h}{R_e}\cos\frac{Vt}{R_e+h}}}, \tag{10}$$

where $t$ denotes the accumulated time of terrestrial user equipment accessing to the LEO satellite.

## III. Modular Design of Physical Layer in ULSNs

In this section, we introduce the physical layer modules of DVB-S2/S2X and DVB-RCS2 standards, supporting multiple MCSs for communications in ULSNs.

### A. DVB standards

DVB-S2/S2X defines the physical layer protocols including channel coding, interleaving and modulation used for satellite communications [13].

1) *Channel coding*: The forward error correction (FEC) of DVB-S2/S2X is in the cascade form of the Bose-Chaudhuri-Hocquenghem (BCH) code which is used as outer code and low-density parity-check (LDPC) code.
2) *Interleaving*: Interleaving rearranges and disperses consecutive bits to mitigate the impact of burst errors and improve overall system performance.
3) *Modulation*: The modulation formats of DVB-S2/S2X implements quadrature phase shift keying (QPSK), amplitude phase shift keying (APSK) from 8APSK to 256APSK.

DVB-RCS2 is compatible with the forward link of DVB-S2 and has significant enhancements in control signaling [14] containing three typical modes:

1) *Forward link (FL) mode*: FL extends in Reed-solomon (RS) code and raptor code with APSK.
2) *Turbo coding-linear modulation (TC-LM) mode*: TC-LM combines the advantages of Turbo coding with linear modulation supporting four TC-LM modulation formats: Binary Phase Shift Keying (BPSK), QPSK, 8-Phase Shift Keying (PSK) and 16-Quadrature Amplitude Modulation (QAM).
3) *Convoluation coding-continuis phase modulation (CC-CPM) mode*: CC-CPM uses continuous phase modulation as the base modulation method and convolutional coding as the error correction coding scheme.

On the basis of DVB-S2X standard in ULSN, this paper realizes ACM strategy including Signal-to-Noise Ratio (SNR) estimation and adaptive MCSs choosing. The ACM strategy dynamically adjusts the parameters of MCS based on the estimated SNR to optimize the data transmission over the LEO satellite-terrestrial channel. The link layer architecture of transmitter and receiver under DVB-S2/S2X standard with ACM strategy is shown in Fig. 2.

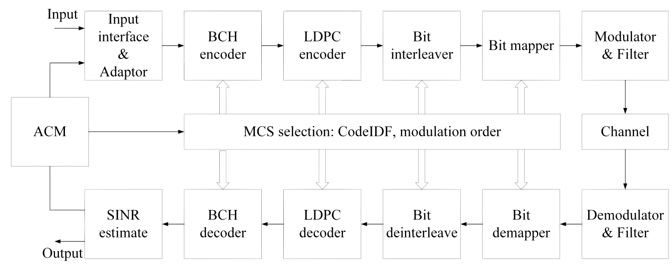


Fig. 2. Transmitter and receiver architecture of DVB-S2/S2X with ACM strategy in ULSN.

The transmitter sends data according to the MCS parameters including LDPC code identifier (codeIDF) and modulation order decided by ACM strategy. The codeIDF in DVB-S2/S2X determines the code word length and message bit length of BCH in DVB-S2/S2X schemes and the error correction matrix of LDPC according to table 9 in DVB-S2/S2X standards [13]. Meanwhile, modulation order along with codeIDF determines the bit mapping scheme in DVB-S2/S2XChannel.

To adopt the ACM strategy at the transmitter, channel state information (CSI) is required [15]. In link-level simulation of ULSNs, channel quality indicator (CQI) is chosen as the representative of CSI. By the CQI feedback, the transmitter selects one of 89 MCSs of DVB-S2/S2X of normal FECFRAME. Meanwhile, the receiver receives the data and performs timely SNR estimation based on the received data employing minimum mean square error (MMSE) algorithm. Then CQI is obtained based on the estimated SNR by the receiver and sent to the transmitter as feedback.

### B. Modular procedure

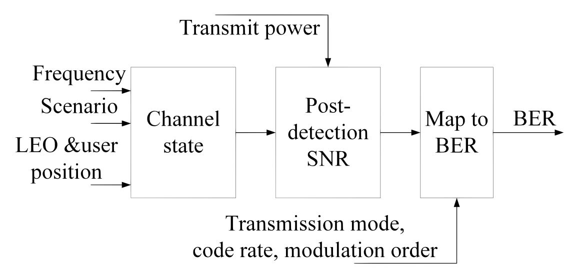


Fig. 3. Modular procedure of Link-level simulation in ULSNs.

Modular link-level simulation serves as a versatile tool for evaluating the performance of physical layer techniques in ULSNs. In the depicted link-level simulation flowchart as shown in Fig. 3 for ULSNs, the BER evaluation process can be methodically delineated into three principal stages as follows.

(1) Channel State Computation: The simulation initiates by parameters such as the carrier frequency, simulation scenario, the position of LEO satellite and terrestrial user equipment. These parameters are integral to generate the channel state according to the channel model set up in Section II. Subsequent

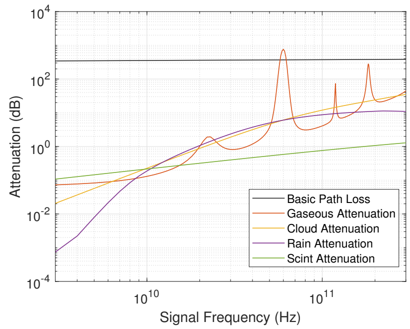


Fig. 4. Various attenuation values at carrier different frequencies.

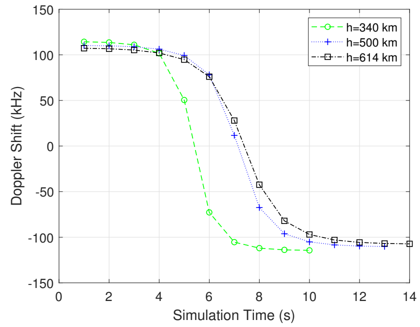


Fig. 5. Doppler shift for different orbit height of LEO satellite.

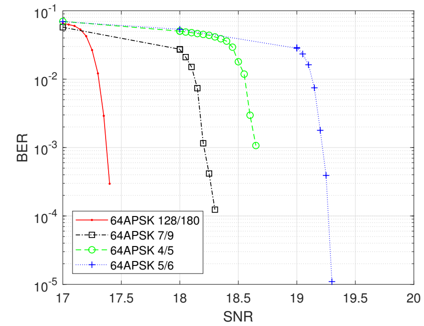


Fig. 6. BER of DVB-S2/S2X of different LDPC rate.

to the channel state assessment, the simulation advances to ascertain the post-detection SNR analyzing the received signal.

(2) MCS Simulation: The detailed MCS simulation process is similar to the flow in Fig. 3, where demodulation is based on log-likelihood ratio algorithm and decoding of CC and Turbo code is based on the log-domain BCJR algorithm [15]. The BER can be obtained based on the simulation which is the simulation's end output.

(3) Mapping between SNR and BER: The final stage entails mapping the estimated post-detection SNR to a BER value which establishes a connection between CSI and physical layer performance. This mapping is influenced by both the initial parameters of channel state computation and the transmission parameters of MCS, which can be used as the physical layer results in the system-level simulations [5].

## IV. Simulation

To introduce capabilities of our simulator and offer increased insights in its functionality, we simulate the state of LEO satellite-terrestrial microwave channel of both UHF and EHF. Moreover, the BER of different DVB protocols are also simulated in the designed link-level simulation platform. Main simulation parameters are shown in Table I.

TABLE I
SIMULATION PARAMETERS

| Parameters | Value |
|---|---|
| Scenarios | 'dense urban', 'urban', 'suburban and rural' |
| Frequency $F_c$ | [3,300] GHz |
| Elevation angle $\alpha$ | [45°,90°] |
| Orbit height $h$ | [340,614] km |

Fig. 4 shows various attenuation values at carrier different frequencies. The basic path loss shows a linear relationship with frequency, and the free space loss is much larger than the clutter loss and shadow fading in the basic path loss. Gas attenuation is frequency selective, with peaks at some specific frequencies. Cloud attenuation has an approximately linear relationship with frequency in the UHF region. Rain attenuation increases with frequency and tends to level off in the EHF region. Scintillation loss shows an approximately linear relationship with frequency. For satellite-terrestrial UHF communication, rain attenuation and cloud attenuation are the main influencing factors in regions with large annual precipitation; in other regions, the four attenuation levels are comparable, all below 0.5 dB. For satellite-terrestrial EHF communication, atmospheric attenuation is the main influence factor. The total attenuation is frequency-selective, showing a peak shape at some specific frequencies.

Fig. 5 shows the maximum variation of the Doppler shift with the motion of LEO satellite. The orbit height of LEO satellite is considered from the Starlink's deployment plan for LEO satellites, raging from 340 km to 614 km. It can be seen that the Doppler shift decreases and then increases during the time that terrestrial user equipment is accessing the LEO satellite. The Doppler shift decreases as the altitude of the LEO satellite orbit increases. This is due to the fact that as the altitude of the LEO satellite orbit increases, the operating speed of the LEO satellite decreases. The increase in orbital altitude will come with greater path loss, but it will reduce the frequency shift of the signal transmission.

Fig. 6 shows the BER of DVB-S2X standard under different LDPC rate. It can be seen that when the code rate is lower the BER is lower. This is because the code rate is defined as the length of the information codeword divided by the length of the coded codeword. A lower code rate results in higher redundancy, enhancing error correction ability and lowering the BER. Meanwhile, Fig. 7 shows the BER of DVB-S2X standard under modulation order. For the same SNR condition, the BER is usually reduced. In general, a smaller modulation order can provide better BER performance at high SNR conditions and reduce the signal's exposure to noise and interference, thus improving the reliability of the system. However, a larger modulation order may provide higher spectral efficiency because it allows more information to be transmitted within a limited spectrum.

Fig. 8 shows the BER of the aforementioned DVB standard and transmission modes. In the context of the DVB-RCS2 return link, the utilization of TC-LM and CC-CPM manifests a lower BER when compared to the forward link and existing DVB-S2/S2X standards. This approach stands out in comparison to traditional forward links and existing DVB-S2/S2X

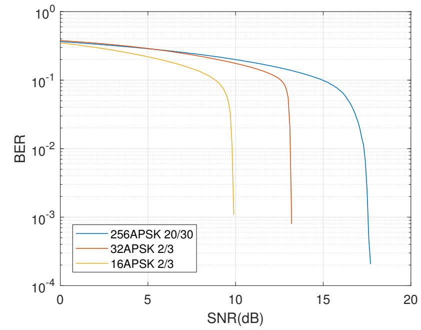


Fig. 7. BER of DVB-S2/S2X of different modulation order.

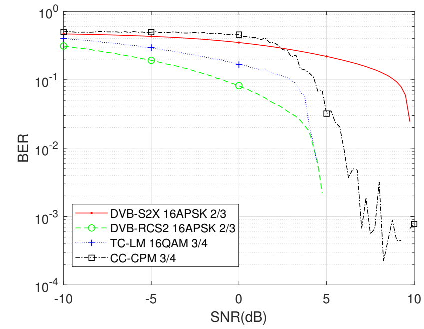


Fig. 8. Modular architecture for link-level simulation in ULSNs.

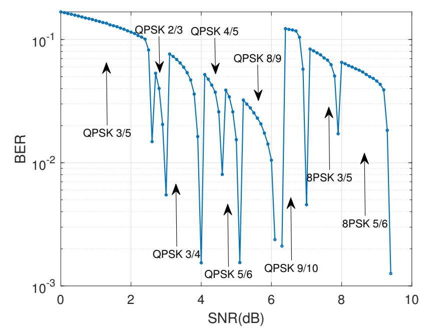


Fig. 9. ACM strategy for DVB-S2/S2X in ULSNs.

standards, emphasizing the importance of tailored modulation and coding strategies in optimizing the performance of satellite communication systems.

Fig. 9. depicts the relationship between BER and SNR of ACM under DVB-S2/S2X standard when SNR ranges from 0 to 10 dB. It can be observed that with the increase in SNR, ACM tends to switch to higher modulation orders or higher data rates, effectively reducing system complexity while maintaining a low BER. This means that ACM can rationalize the choice of MCS scheme to balance the BER performance with the system complexity. Moreover, the overall BER of ACM is low, and the BER situation exists only at low SNRs.

## V. Conclusion

In this paper, we have provided a versatile self-developed simulator for the link-level performance analysis of DVB standards in ULSNs. Specifically, we have presented a comprehensive model for the satellite-terrestrial microwave channel taking into account rain attenuation, cloud attenuation, and Doppler frequency shift. We have delved into the implementation for physical layer of DVB standards encompassing various physical layer MCSs and extending our efforts to the realization of ACM. Finally, we have conducted comparative performance analysis using the established channel models to assess the effectiveness of different MCSs of DVB standards. Simulation results have been envisioned to provide valuable insights for further exploration of physical layer protocol design in ULSNs. In the future, we will explore advanced physical layer methods for satellite-terrestrial microwave communications considering interference between users.

## Acknowledgment

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