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Link adaptation techniques for throughput enhancement in LEO satellites: a survey

Habib Idmouida, Khalid Minaoui
LRIT Laboratory, Faculty of Sciences, Mohammed V University in Rabat, Rabat, Morocco
University Center for Research in Space Technologies, Mohammed V University in Rabat, Rabat, Morocco

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ABSTRACT

In addition to the rapid geometric change of low earth orbit (LEO) satellites, the earth-to-space channel suffers from various attenuations that affect the communication link. To overcome this challenge, the link adaptation technique emerges as a key solution to optimize the transmission performance of LEO satellites, especially the data throughput. The existing contributions in the literature remain scattered across the research board, and a comprehensive survey of this research area still lacks at this stage. The present survey examines various link adaptation methods, mainly variable coding and modulation, adaptive coding and modulation, and hybrid methods using artificial intelligence. In addition, this study explains how this technique leverages a set of recommended standards and cost-effective technologies, such as software-defined radio (SDR) and field programmable gate arrays (FPGA), to fine-tune transmission strategies. Lastly, the paper provides a comparative study of the current research on this field and sheds light on future directions, where the need for higher data throughput makes emerging learning-based techniques and new experimental standards a necessity.

Corresponding Author:

Habib Idmouida
LRIT Laboratory, Faculty of Sciences, Mohammed V University in Rabat
Agdal, Rabat, Morocco
Email: habib_idmouida@um5.ac.ma

1. INTRODUCTION

With the advancement in space technology, the low earth orbit (LEO) has been employed for high data rate (HDRT) applications because of its proximity to the earth (approximately 200–1,000 km) [1]. In this scope, modern satellite designs, including small satellites, microsatellites, nanosatellites, picosatellites and CubeSats have gained attention from New Space as they offer new technologies with affordable prices and short development times [2]. The majority of LEO satellites are used for different purposes, such as remote sensing, earth observation, space exploration and even military applications [3]. These satellites feature various subsystems, mainly the communication subsystem, and collect different types of data to be processed, analyzed and eventually sent to ground stations. Nevertheless, a fixed ground station can maintain contact with a passing LEO satellite for only 10% of the overall in-orbit time due to their high velocity (7.8 km/s), resulting in a short visibility duration of 10 min. Moreover, direct links between a LEO satellite and a ground station suffer from many impairments and attenuations that reduce the transmission performance [4]. Therefore, the development of reliable and efficient communications with enhanced data throughput is becoming ever more critical and requires pioneering solutions to meet the growing demand of HDRT applications. Thus, many methods can be used to access more bandwidth with high data throughput, such as applying advanced data compression algorithms to reduce the size of data before transmission [5], upgrading ground stations with high-capacity antennas as diversity techniques [6] or utilizing high order modulation techniques combined with advanced coding schemes [7]. However, these solutions address significant design challenges related to hardware, size, power, thermal management, and reliability. To deal with this issue, link adaptation can be used as fade mitigation techniques to improve transmission performances of LEO satellite systems [8].

In wireless communication systems, link adaptation is a technique used to adjust the link parameters, such as the modulation scheme, the error correction, the coding rate or the data rate based on the propagation channel conditions, where the link quality can vary due to factors like distance and environmental conditions. This adaptive approach encompasses variable coding and modulation (VCM), adaptive coding and modulation (ACM), and hybrid methods that employ artificial intelligence (AI)-based strategies to predict and determine the channel state information (CSI) [9]. This technique has proven to be a successful method in Wi-Fi networks such as IEEE 802.11 wireless local area network (WLAN) [10], wireless cellular networks such as long-term evolution (LTE) and fifth generation (5G) [11], satellite communications [12], and television broadcasting systems [13]. Following this advancement, the space industry is progressing towards standardizing link adaptation for non-geostasionary (NGSO) satellites. Recent research is increasingly focused on implementing adaptive transmissions since the European Telecommunications Standards Institute (ETSI) and the Consultative Committee for Space Data Systems (CCSDS) have established a set of recommended standard protocols to be applied in small satellites for HDRT applications [14]. To this end, the implementation of link adaptation on LEO satellites takes place on the field programmable gate arrays (FPGA) model and software-defined radio (SDR). These technologies can provide faster processing with fewer computational resources, even in harsh radiation environments [15].

As far as we know, no previous research has reviewed the application of link adaptation in LEO satellites with a focus on data throughput enhancement. The current essay provides a comprehensive survey of this technique and assesses reviewed methods by comparing their advantages and shortcomings. Following a succinct introduction in section 1, section 2 describes the link adaptation principle, methods, standardization and implementation in LEO satellites. Section 3 presents a literature survey of the current research. Section 4 provides the discussion of the findings. Finally, section 5 concludes the survey with potential future directions.

2. PRINCIPLE OF LINK ADAPTATION IN LEO SATELLITE SYSTEMS

The topology of small satellites is highly dynamic depending on the LEO geometry. The satellite's motion can be considered as a short visible arc segment, and the associated elevation angle θ and distance S vary proportionally, as shown in Figure 1. Hence, the strongest signal is received when the satellite is above the ground station at high elevations, while the weakest signal is attainable at low elevations [16]. Generally, satellite communications employ constant coding and modulation (CCM) to guarantee a reliable transmission even with the worst-case link budget. However, this approach often results in underutilization of available resources when channel conditions improve. Thus, the selection of forward error correction code (FEC) and modulation technique is crucial and profoundly impacts system metrics such as signal-to-noise ratio (SNR), carrier-to-noise ratio (CNR), link margin, and bit error rate (BER) [17].

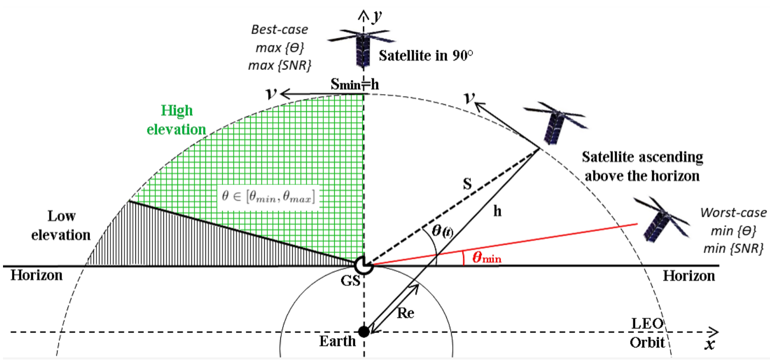

Figure 1. LEO satellite geometry

In this perspective, link adaptation is a key solution to adapt the modulation and coding schemes (MCS) to the variations of the radio link. Practically, higher throughput is attained during optimal channel conditions by employing higher modulation orders with less error correction. In contrast, throughput diminishes as the radio requires a higher level of error correction and more robust modulation with low orders when link conditions are poor. Figure 2 depicts how link adaptation mechanism responds to varying channel conditions.

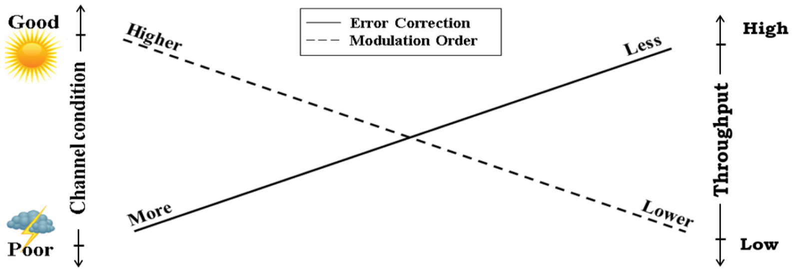

Figure 2. Link adaptation mechanism

2.1. Link adaptation methods and implementation

The link adaptation methods used in LEO satellites encompass VCM, ACM, and hybrid methods that combine link adaptation with AI algorithms. The VCM method enables a rapid switching of the MCS considering deterministic environmental changes of the elevation angle and distance between the satellite and the ground station. Hence, the VCM method leverages additional link resources to adjust the MCS based on predefined thresholds. While the ACM expands the VCM method by dynamically adjusting the MCS to non-deterministic channel conditions. To this end, the signal quality is extracted based on the CSI knowledge. This CSI can be estimated through the periodic insertion of known pilot symbols into the information symbols. At the receiver input, the channel state is derived from these transmitted pilot symbols and received ones, considering transmission metrics such as SNR, CNR, BER, or link margin. Then, the CSI is relayed back via a feedback channel to the transmitter side, which dynamically adapts the MCS to prevailing channel conditions [18]. The diagram in Figure 3 illustrates the process of an end-to-end adaptive transmission for LEO satellites.

Nevertheless, traditional link adaptation struggles with accurate CSI estimation and synchronization issues when the feedback is outdated. To address this limitation, AI-based algorithms offer a practical alternative by predicting the CSI or autonomously selecting the most suitable MCS in real-time. The application of AI has shown great results in terms of precision and accuracy for more reliable transmission in wireless communication systems. In practice, this approach combines the ACM method with machine learning (ML), deep learning (DL) and reinforcement learning (RL) techniques to optimize the process of link adaptation [19].

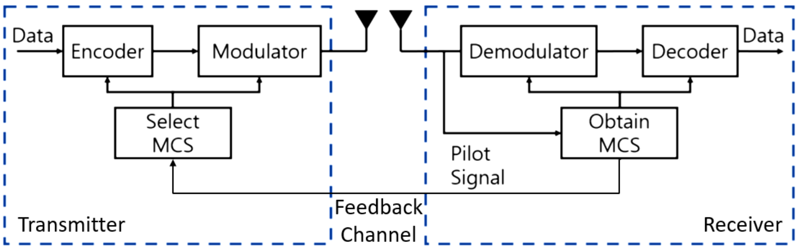

Figure 3. Diagram of end-to-end adaptive transmission for LEO satellite

In the last decade, signal processing has witnessed remarkable utilization of software systems for satellite communication implementation. This evolution has led to the emergence of SDRs, where a substantial part of digital signal processing (DSP) is executed by general-purpose processors (GPP) and FPGAs [20]. Thanks to their modularity, extensibility and flexibility, the SDR technology can be used for link adaptation implementation only through software modifications. Zeedan and Khattab [15] reviewed the commercial and custom SDR transceiver architectures on-board small satellites existing in the literature. Commercial SDRs are flight-proven and enable higher data rates but at higher costs, while custom SDRs perform well overall with lower costs and complexity. SDRs encompass a programmable DSP unit for signal processing and an acquisition unit that connects the baseband processor to radio frequency (RF) front ends through digital interfaces (analog-to-digital converter (ADC) and digital-to analog converter (DAC)). Figure 4 depicts the architecture of an SDR-based transceiver for LEO satellites.

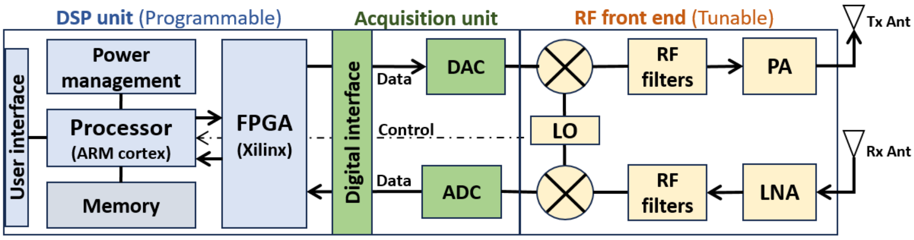

Figure 4. SDR based tranceiver architecture for LEO satellites

2.2. Link adaptation standardization

The advancement of new technologies in LEO satellites pushed the European Space Agency (ESA) to approve the adoption of standard protocols for link adaptation in NGSO satellites through CCSDS recommended standards. The first recommended standard 'CCSDS 131.0-B-2' defined a range of advanced FEC codes (turbo, reed-solomon, convolutional, low-density parity-check (LDPC)) to be used with various modulation techniques like binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), and Gaussian minimum shift keying (GMSK) [21]. The second recommended standard is 'CCSDS 131.2-B-1' and covers 27 MCS using serially concatenated convolutional codes (SCCCs) combined with high order modulation schemes such as QPSK, 8-PSK and 16/32/64-APSK [22]. Then, the 'CCSDS 131.3-B-2' standard integrates CCSDS space link protocols with the digital video broadcasting by satellites second generation (DVB-S2). This standard supports 28 MCS based on the valid combinations between four modulation schemes (QPSK, 8-PSK and 16/32-APSK) and concatenated codes using Bose-Chaudhuri-Hocquenghem (BCH) and LDPC codes [23]. Finally, a generic standard 'CCSDS 431.1-B-1', known as 'Variable Coded Modulation Protocol', provides a uniform strategy by mixing different combinations of MCS from the aforementioned standards [24]. These recommended standards follow the open systems interconnection (OSI) model, as illustrated in Figure 5.

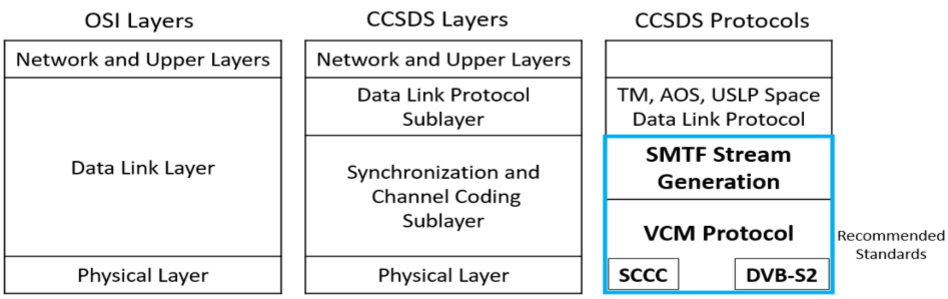

Figure 5. Relationship between CCSDS protocols and OSI model

The CCSDS protocols cover the 'Data Link Protocol Sublayer', the 'Synchronization and Channel Coding Sublayer' of transfer frames and the 'Physical Layer' dedicated to modulation methods for bit stream transfer over space links. The process of link adaptation functions initially through synch-marked transfer frames (SMTFs) stream generation after pseudorandomizing the transfer frames. These SMTFs are sliced into blocks of encoder-input size and then encoded with FEC codes, resulting in modulation symbols of the encoded data. Additionally, the physical layer frame (PLFRAME) header is prepended, with the option to insert pilot signals with the modulated symbols for data transfer over the RF channel, as depicted in Figure 6.

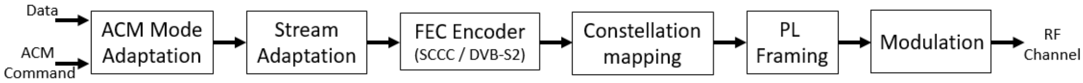

Figure 6. CCSDS functional diagrams of adaptive transmitter

3. LITERARY SURVEY OF CURRENT RESEARCH

In recent developments, numerous industrial and academic research initiatives have introduced link adaptation for throughput enhancement in LEO satellites. This paper is the result of a review process involving rigorous identification, scanning, and eligibility testing. Initially, our search spanned journal and conference papers published between 2019 and 2024 across prominent databases including Google Scholar, IEEE, Elsevier, MDPI, Ipmugo and Wiley libraries. The systematic search relied on keyword combinations of 'link adaptation', 'LEO satellite', 'CCSDS', 'VCM', 'ACM', 'throughput', 'CSI' and 'AI' to identify the most pertinent papers. Ultimately, thirty papers were meticulously selected and subjected to thorough analysis.

3.1. Variable coding and modulation methods

The initial VCM demonstration was conducted by the Jet Propulsion Laboratory (JPL) against multipath and shadowing caused by the International Space Station structures using the space communications and navigation (SCaN) Testbed. In this testbed, the JPL deployed a SDR based on Xilinx Virtex II FPGA and SPARC GPP to implement VCM over DVB-S2, which reached a peak datarate of 2.226 Gbps [25]. The CubeSat Communications Platform (CCP) team and NASA's Near Space Network (NSN) implemented the VCM method over CCSDS and VITAMIN (variable-coded modulation to maximize information) protocols using commercial SDR and demonstrated a noteworthy enhancement of 50% in data throughput [26]. Subsequently, Zhang *et al.* [27] upgraded an X-band transmitter by integrating the VCM method over the DVB-S2 standard in remote sensing CubeSats. This transmitter exhibited 42.1% throughput increase during a single pass. Kang *et al.* [28] proposed an efficient FEC encoder based on the Xilinx XC7K325t FPGA to support the DVB-S2 standard that showed a 30.9% improvement for an encoding rate of 1.19 Gbps. In this approach, the VCM method adapats the MCS combinaison during the satellite pass by considering three elevation angle sectors. Liu *et al.* [29] tested a DVB-S2/LDPC encoder architecture on the Xilinx Kintex-7 FPGA with a recursive encoding core for fast computations. The results of this optimized encoder achieved a high data throughput of 47.5 Gbps with a clock frequency of 280 MHz. Moreover, Li *et al.* [30] proposed a VCM-based downlink method for the Gaofen-7 EO satellite using a DVB-S2 BCH-LDPC encoder that achieves a maximum channel datarate of 3.5 Gbps. Quintarelli *et al.* [31] proposed a novel architecture for a DVB-S2 BCH encoder using a configurable datapath. In this architecture, the VCM method was implemented using the Xilinx Kintex Ultrascale XQRKU060 FPGA and demonstrated an optimized data throughput from 600 Mbps to 19.2 Gbps. Al Mahmood *et al.* [32] developed a VCM framework to vary the MCS combinaison of the DVB-S2 standard for 1-unit CubeSat that substantially increased the data throughput by 250%.

3.2. Adaptive coding and modulation methods

As aforementioned, the ACM method has the advantage of adapting dynamically the MCS based on measured metrics. Within this context, The planet mission customized SDR using commercial off-the-shelf (COTS) technology to showcase the ACM method over DVB-S2 in a 3-unit CubeSat operating at X-band [33]. In this study, the ACM method combines the link margin and a safety margin as metrics, to achieve a peak data rate of 1.6 Gbps with 80 GB of data capacity per pass. Mendoza *et al.* [34] proposed a new DVB-S2 transmitter operating at X-band to forward video in real-time from CubeSats. This ACM-based transmitter utilizes a high-performance FPGA 'Zynq 7020' implemented in commercial TOTEM SDR from Alén Space. As a result, the CubeSat could download 13.2 GB of high-quality video data in a single pass. Inceoz *et al.* [35] developed an FPGA-based SCCC encoder for LEO satellites based on the Xilinx Kintex Ultrascale XCKU060 FPGA, which combines different MCS and enables to reach a data rate output of 530 Mbps. Meoni *et al.* [36] implemented a VHDL telemetry transmitter IP Core fully compliant with the CCSDS 131.2-B-1 standard to support the ACM method. In this work, the design of the IP core transmitter was based on a Microsemi RTG4 FPGA and showed a high data rate of 1.355 Gbps. The Institute of Space Systems developed an adaptive X-band transmitter compliant with the CCSDS standards [37]. This transmitter supported ACM mode with data rates up to 200 Mbps using the Zynq-7020 FPGA matched with a dual-core processor, resulting in a

130% enhancement in downlink data throughput. In addition, Cuervo *et al.* [38] proposed a new ACM-based approach compliant with the CCSDS 131.2-B-1 standard for Q-band end-to-end systems. This approach could improve the data throughput of EO satellite missions by 90.3%. Wang *et al.* [39] introduced a new metric for the ACM method, known as the transmission efficiency factor (TEF), which considers the link availability and useful data rate. This adaptive approach demonstrated a throughput improvement of 24.51% against weather variations. Finally, Nannipieri *et al.* [40] proposed a fully compliant DVB-S2 LDPC encoder for a high data-rate downlink telemetry system in the context of earth exploration satellite service. This encoder supports the ACM method utilizing the XQRKU-060 FPGA to optimize transmission efficiency and could reach a reconfigurable throughput from 0.52 to 21 Gbps.

3.3. AI-based link adaptation methods

Recently, the research community has directed its focus towards AI-based methods to optimize link adaptation processes. In this context, NASA utilized a neural network-based reinforcement learning (RLNN) on the SCaN testbed to showcase the potential of a cognitive engine for real-time MCS selection [41]. Then, Wang *et al.* [42] employed k-nearest neighbour (KNN) and multi-layer perception (MLP)-based algorithms to predict future CSI and increase the average throughput by 10.9%. Bai *et al.* [43] proposed the use of artificial neural networks (ANNs) to estimate fading in Q-band and could achieve real-time fading estimations with a probability exceeding 98.8%. Guo *et al.* [44] proposed a new auto-regressive integrated moving average (ARIMA) based on historical CSIs to predict future CSIs with higher accuracy than conventional models using long short-term memory (LSTM) networks. Almalki and Othman [45] proposed an ANN framework for CubeSat communications at K-band to predict joint effects of atmospheric and dust attenuations in Gulf Cooperation Council (GCC) countries in order to support internet of things (IoT) connectivity using the ACM method. Furthermore, Zhang *et al.* [46] presented a DL-based prediction technique through a satellite channel predictor (SCP) in massive multiple-input multiple-output (MIMO) systems using a CNN-LSTM model and then suggested deep neural networks (DNNs) to predict future downlink channel states from observed uplink states for LEO satellites with massive MIMO technology [47]. Zhang *et al.* [48] introduced a DL-based weather-aware ACM approach for accurate channel estimation using deep eeinforcement learning (DRL) method for intelligent ACM decision-making. By integrating real-time global weather and historical channel information, the proposed model demonstrated accurate channel estimations and intelligent pre-switching of coding schemes. Additionally, they proposed an LSTM-based ACM method for predicting the most accurate SNR, factoring in past channel status and real-time global weather. This model exhibited a high overall measurement rate for accurate channel prediction [49]. Ortiz *et al.* [50] introduced a DL-based CSI prediction framework to predict signal quality through time series data in future NTN-integrated 6G networks. This prediction strategy enables the development of an efficient ACM mechanism by training a regression LSTM network to adapt MCS to the signal quality. Kang *et al.* [51] proposed a channel estimation scheme using ML-based denoising networks for massive multi-input single-output (MISO) systems. In this work, a denoising CNN (DnCNN) was employed to improve the accuracy of the CSI by reducing least squares (LS) channel estimation errors. Finally, Wang *et al.* [52] proposed a LSTM network model for enhancing the accuracy of the CNR prediction by estimating the satellite position in its orbit.

4. RESULTS AND DISCUSSION

4.1. Comparison of link adaptation techniques

In this paper, we performed a thorough analysis of link adaption techniques utilized in LEO satellites for throughput enhancement. Initially, our investigation evaluated the outcomes of the VCM and ACM methods concerning their applications, standards, and implementations, as detailed in Table 1.

The comparison shows that eight of the reviewed techniques used the VCM method, and eight used the ACM method for various applications such as Earth observation, CubeSat communication, and technology demonstration. The implementation process of link adaptation was performed using SDRs with FPGAs from Xilinx and microsemi families that have achieved flight heritage on many programs. For the data throughput, ten systems reach more than 1 Gbps, four systems have a data rate between 100 Mbps and 1 Gbps, and only two systems transmit with less than 100 Mbps. It can also be noted that thirteen systems employ the CCSDS 131.3-B-2 standard, while only three systems adopted the CCSDS 131.2-B-1 standard. In addition to VCM and ACM methods, twelve systems proposed AI-based methods to optimize the link adaptation process. Ten of them used DL methods based on ANN, DNN, DCNN, RLNN, LSTM and DRL algorithms, while only two systems made use of ML based on CNN, KNN and MLP algorithms. All these systems lead to optimized link adaptation in various applications by improving the accuracy of different metrics prediction. Table 2 provides a comparative study of various AI-based methods for link adaptation optimization.

Table 1. Comparison of reviewed systems based on VCM and ACM methods in LEO satellites

Ref/year	Method/standard	Technology	Application	Data throughput	Outcomes
[25]/2016	VCM/DVB-S2	SDR	SCAN Testbed	2.226 Gbps	+2.7 dB of link capacity
[26]/2019	VCM/DVB-S2	SDR	Technology demonstration	109 Mbps	+50% throughput
[27]/2020	VCM/DVB-S2	SDR	Remote sensing	787 Mbps	+42.1% throughput
[28]/2020	VCM/DVB-S2	XC7K325t FPGA	Technology demonstration	1.19 Gbps	+30.9% throughput
[29]/2022	VCM/DVB-S2	Kintex-7 FPGA	Technology demonstration	47.5 Gbps	Resource optimization
[30]/2023	VCM/DVB-S2	SDR	Earth observation	3.5 Gbps	+16% throughput
[31]/2023	VCM/DVB-S2	XQRKU060 FPGA	Earth observation	19.2 Gbps	Resource optimization
[32]/2024	VCM/DVB-S2	SDR	CubeSat communication	3.68 Mbps	+250% throughput
[33]/2019	ACM/DVB-S2	Zynq 7020 FPGA	Earth observation	1.6 Gbps	80 GB per pass
[34]/2020	ACM/DVB-S2	SDR	Video forwarding	50 Mbps	13.2 GB per pass
[35]/2020	ACM/SCCC	XCKU060 FPGA	CubeSat communication	530 Mbps	High spectral efficiency
[36]/2020	ACM/SCCC	RTG4 FPGA	Technology demonstration	1.355 Gbps	+15% throughput
[37]/2021	ACM/DVB-S2	SDR	Technology demonstration	200 Mbps	+66% throughput
[38]/2021	ACM/SCCC	SDR	Earth observation	750 Mbaud	+90.3% throughput
[39]/2022	ACM/DVB-S2	SDR	CubeSat communication	2.468 Gbps	+24.51% throughput
[40]/2024	ACM/DVB-S2	XQRKU-060 FPGA	Earth exploration	21 Gbps	Resource optimization

Table 2. Comparison of AI-based methods for link adaptation optimization

Ref/year	Method	Technique	Application	Improvement
[41]/2019	DL	RLNN	Deep space operation	MCS selection
[42]/2019	ML	KNN and MLP	Satellite networking	CSI prediction
[43]/2019	DL	ANN	Satellite communication	Fading estimation
[44]/2020	DL	LSTM	6G network	Future CSI prediction
[45]/2021	DL	ANN	IoT connectivity	Attenuation prediction
[46]/2021	DL	CNN and LSTM	MIMO technology	CSI prediction
[47]/2022	DL	DNN	MIMO technology	CSI prediction
[48]/2022	DL	DRL	Ubiquitous network	CSI prediction
[49]/2022	DL	LSTM	Satellite communication	SNR prediction
[50]/2023	DL	LSTM	6G network	Signal quality prediction
[51]/2023	ML	DnCNN	MISO technology	CSI prediction
[52]/2023	DL	LSTM	Satellite networking	CNR prediction

4.2. Discussion

Link adaptation techniques are very useful in satellite data links thanks to their capacity to meet the requirements of HDRT applications by enhancing the data throughput. Each reviewed method has its advantages and limitations. The VCM methods adapt the MCS based on its prediction of link conditions and were discussed in [25]–[32], while ACM methods were discussed in [33]–[40] as an extension of VCM methods to enable better throughput performance. The obtained results of NASA programs [25], [26] demonstrate that these methods over DVB-S2 were successful in enhancing the overall throughput performance using high-capability testbeds. However, the optimization of resource utilization is particularly noteworthy and must be considered in small satellites with limited resources. Therefore, many authors proposed different architecture designs of BCH and LDPC encoders to achieve a higher performance index with fewer resources. The proposed BCH encoder presented in [31] can provide a good throughput with a maximum power consumption of only 79 mW. In other ways, higher data throughput can be achieved using LDPC encoder architectures, as presented in [29], [40]. These architectures are more resource-efficient and perform better at higher code rates, but the conversion of LDPC encoder inputs, which often come from BCH encoders, into the required parallel format is still challenging. An alternative solution was proposed in [28], [30], [32], [37] and suggested a conventional FEC encoder, which consists of a concatenation of BCH and LDPC codes. Hence, the input and output interfaces of this encoder will be designed for high reconfigurability and integration. Otherwise, FPGA-based SCCC encoder architectures for flexible telemetry transmitters were highlighted in [35], [36], [38] and performed better flexibility and efficient resource utilization. The proposed architectures were implemented in Xilinx and Microsemi FPGAs using VIVADO and VHDL for synthesis and analysis. Nonetheless, VCM and ACM methods are commonly referred to as limited feedback systems and supply accurate channel state knowledge. Therefore, link adaptation combined with AI models has produced more accurate outcomes [41]–[52]. This hybrid approach combines different ML, RL and DL algorithms and may increase the accuracy using larger data sets for model training. In many cases, the drastic changes in channel conditions may disable the CSI prediction accuracy. The observation indicates that ML prediction models in [41], [51] are performed through offline training, and results during communication operations could remain unchanged. Hence, DL-based systems presented in [49], [50], [52] can learn about themselves and their environment for real-time adaptation. This real-time adjustment can also be fulfilled by RLNN, DNN or LSTM frameworks presented in [41], [44], [47].

5. CONCLUSION AND FUTURE DIRECTIONS

Link adaptation has emerged as a prominent strategy in LEO satellites to meet the growing demand for HDRT applications. This paper presents a review study on link adaptation methods, detailing their implementation using cost-effective technology and recommended standards. The reviewed systems have demonstrated that SDR and FPGA are the most suitable technology to achieve high throughput with significant flexibility and optimized resource utilization. The survey also identifies the CCSDS recommended standards approved by a majority of the world's space agencies for link adaptation implementation in NGSO satellites. In addition, the paper highlights AI-based methods that leverage various ML, RL and DL algorithms in order to improve the accuracy of signal quality prediction and optimize the process of link adaptation. As far as future challenges in this research area, the authors of this paper believe that emphasis should be given to the implementation of new CCSDS experimental specifications (DVB-S2X and SCCC-X extension), which are still rarely used. In addition, attention should also be paid to the utilization of link adaptation with millimeter and terahertz waves and their validation before flight with electrical ground support equipment (EGSEs), fully compliant with CCSDS standards. Finally, an intriguing prospect is to involve automatic modulation classification (AMC) in both transceivers and ground stations, which is a promising technique for future satellite cognitive communications.

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BIOGRAPHIES OF AUTHORS

Habib Idmouida was born in Casablanca, Morocco in 1992. He received the Engineer degree in Naval Telecommunications and Radar Engineering in 2014 from the Ecole Royale Navale in Morocco. He is currently a Ph.D. student in Aerospatial Technologies at the Computer Science and Telecommunications Research Laboratory in the Faculty of Sciences of Rabat and a member of the University Center for Research in Space Technologies at Ecole Mohammadia d'Ingenieurs of Rabat in Morocco. His research is focused on satellite link and communication system design. He can be contacted at email: habib_idmouida@um5.ac.ma.

Khalid Minaoui received in 2010 the dual national Ph.D. degree (cotutelle) in signal processing and computer science from Mohammed V University in Rabat (Morocco) and Telecom Bretagne in Brest (France), and the Accreditation to supervise research (HDR) degree in 2014 from Mohammed V University in Rabat. He is currently the director of the Computer Science and Telecommunications Research Laboratory and Professor of Telecommunications Engineering at the Faculty of Sciences, Mohammed V University in Rabat. His research interests are signal processing and applications. He can be contacted at email: khalid.minaoui@um5.ac.ma.