Chukwudi *et al*. / KJSET: Vol. 3, No. 2, (Dec 2024) 39-50. https://doi.org/10.59568/KJSET-2024-3-2-04

KAMPALA INTERNATIONAL UNIVERSITY
KIU
Journal of Science, Engineering and Technology

KJSET Research Article

A comprehensive review of adaptive modulation and coding techniques for spectrum efficiency and interference mitigation in satellite communication

Ogenyi Fabian Chukwudi [1], Mohammed Dahiru Buhari [2], B. O. Sadiq[3], Enerst Edozie[4] and Val Hyginus Udoka Eze[5]

Department of Electrical, Telecommunication and Computer Engineering, Kampala International University, Uganda[1,2,3,4,5]
Electrical and Electronic Engineering Department, Abubakar Tafawa Balewa University, Bauchi, Nigeria[2]

Corresponding Author:chukwudi.ogenyi@studwc.kiu.ac.ug¹

Paper history:
Received 16th October 2024
Accepted in revised form 11th December 2024

Keywords
Frequency Reuse Schemes, FDMA, TDMA, CDMA, AMC, Spectral Efficiency, System Reliability and Resource Allocation.

Abstract

This paper provides a detailed analysis of Advanced Adaptive Modulation and Coding (AMC) techniques in satellite communication and compare it with the conventional frequency reuse system such as Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA), which rely on fixed resource allocation, AMC dynamically modifies modulation and coding rates, optimizing throughput during favorable conditions and ensuring reliability in adverse scenarios. In optimal conditions, spectral efficiency improves by 30-50% due to AMC's adaptability, as governed by Signal to Noise Ratio (SNR) and Bit Error Rate (BER) thresholds. This paper also demonstrates that its integration with machine learning (ML), specifically, deep learning (DL) and deep reinforcement learning (DRL) enables prediction and adaption, which can address challenges such as channel fading and dynamic signal variations in Low Earth Orbit (LEO) satellite network. Traditional methods are outperformed by these data driven approaches for further improving throughput and reliability. While AMC requires sophisticated hardware, complex algorithms, and efficient feedback systems, solutions such as predictive algorithms and hybrid approaches mitigate these challenges. These findings highlight AMC's transformative role in addressing growing demands for higher data rates, efficient spectrum utilization, and robust communication, positioning it as a cornerstone for the future of satellite communication systems in dynamic environments.

1.0 Introduction

In the arena of communication satellite interference, a tough fight is on between typical frequency reuse schemes and cutting edge Advanced Adaptive Modulation and Coding (AMC) [1]. So, let's explore the scenario of the confrontation between technologies and spectral efficiency of the future. FDMA, TDMA and CDMA, the three most important traditional ones, still provide the foundation by allotting fixed frequency bands or time slots, or by implementing unique spreading codes [2-3]. On the one hand, they points out those inefficiencies and challenges, including spectrum wastage, synchronization problems and interference difficulties. Future AMC can dynamically adapt its modulation and coding policies according to the channel conditions and the user needs [1]. This inherent adaptability does not only improve spectral efficiency but at the same time it safeguards system dependability amidst the rough tides of interference [3]. AMC transforms satellite communication market by flexible resource management and smart optimization. As a result, the AMC has greater reliability and efficiency compared to the others [3-5]. In the process of getting rid of interference, the choice between tradition and development is a matter of life and death. Will the time-tested approaches like frequency reuse masks win or do cutting-edge capabilities in Advanced AMC transform satellite communication into a new stage of high performance? The fate of interference suppression, as we know it, heavily relies on how the technology takes shape.

Frequency Reuse Schemes

Frequency reuse is one of the basic techniques which is used in all satellite communication systems to make most efficient use of allocated spectrum [1]. It makes use of spectrally reusing the frequency spectrum by dividing it into multiple channels that are allocated to overlapping geographical ranges [2]. The multiple techniques including FDMA, TDMA, and CDMA have been invented to make the frequency reuse and its purpose feasible [3]. The nature of the plan varies from one approach to another thus providing different interferences of interference [4].

2.1. **FDMA:** Frequency Division Multiple Access assigns dedicated frequency bands for the use of each user or channel, enabling the simultaneous transmission without interference. Within the assigned frequency bands, the users can transmit without interfering with others [5]. On the other hand, the fact that spectrum components are static in location may affect system efficiency, more so in the case of traffic patterns that are unevenly distributed [6].

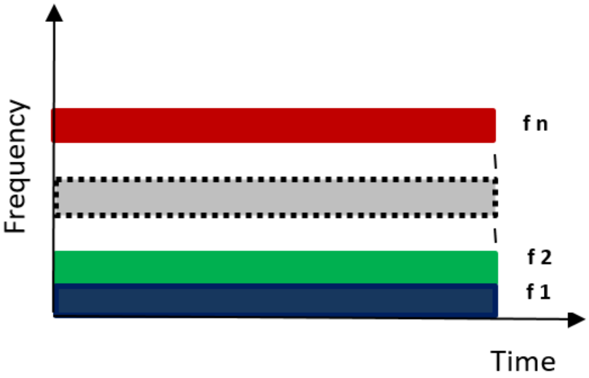


Figure 2.1: Frequency Division Multiplexed signal for satellite Application.

2.2. **TDMA:** In Time Division Multiple Access, pieces of time between these frequency bands are allocated to different users or channels [10]. As TDMA gives equal time to each station dynamically depending upon the demand, it can be adjusted as per the varying patterns of traffic thereby improving the problem of interference [11]. Additionally, these complexity states may lead to synchronization problems and heavy loads of slot allocation that harm the efficiency of the system. [12].

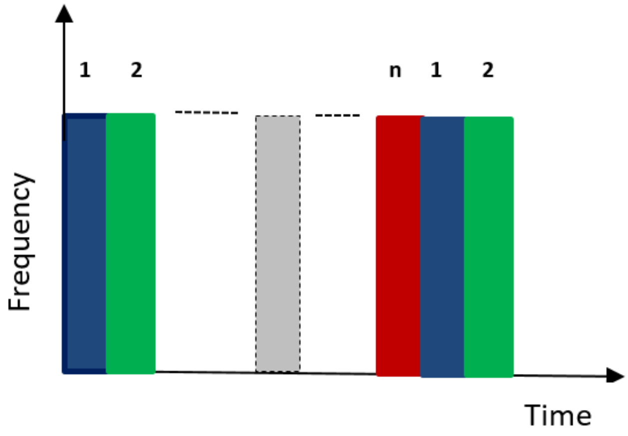


Figure 2.2: Time Division multiplexed signal for satellite TDMA Application.

2.3. CDMA: Code Division Multiple Access makes the transmission of diversified messages of different users possible in the same frequency band by using exclusive spreading codes [13]. CDMA works by taking advantage of code ortogonality, which is used at the receiver to separate signals [14]. On the other hand, the combination of many overlapping signals makes the issue such as multi-user interference and code synchronization possible [15].

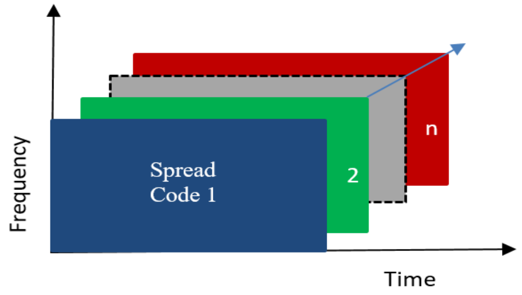


Figure 2.3: Code Division Multiplexed signal for Satellite CDMA Application

Summary of Fig, 1, 2, and 3

Frequency reuse approaches (FDMA, TDMA, and CDMA) are fundamental in satellite communications in order to optimize spectrum utilization. All initiatives have the advantages and challenges. FDMA divides frequencies into separate frequency bands between users or channels, thus allowing simultaneous transmission without interference. On one hand, the point-to-point connection via fixed frequency band allocation leads to spectrum inefficiencies, particularly in cases with uneven distribution of traffic flow. TDMA divides time slots of assigned frequency band between many users with changing number of them when demand arises. The dynamicity of this approach is an advantage when handling traffic flow changes, however, the allocation of slots and synchronization issues may degrade system performance. CDMA allows each user to send information over the same frequency band using their unique spreading codes in parallel. It resolves the interference by using code orthogonally and thus generated signals can be separated at the receiver end. The stated techniques for access i.e. FDMA, TDMA, CDMA and their various combinations follow the capacity formula for Shannon Hartley.

$C = B\log_2 (1+ S/N)$

Where C = channel capacity, B= bandwidth allocated S/N = signal to noise Ratio. Logarithmic rise instead of the linear rise is observed when S/N is increased. Yet, multi-user interference and code synchronization are interlinked issues because of similar transmitted signals [4, 7-9].

2.0 Key Concepts of Adaptive Modulation and Coding

Technologies implemented in frequency reuse with the purpose of handling these problems and also of enhancing efficiency [8]. The utilization of cutting-edge AMC schemes is one of the methods the technology is based on. AMC ascertains the optimal modulation and coding transmission parameters depending on the channel conditions, user needs, and system restrictions [11-13]. This method of spectral efficiency is achieved by smartly using the available resources while at the same time reducing the harmful interference and increasing overall system operation [7].

3.1 Adaptive Modulation

Adaptive modulation involves modulation of signals in accordance with the quality of the channel through which the signals are transmitted [8-10]. Adaptive transmission involves the variation of modulating techniques on the information signal in relation to the quality of the channel that is used in transmitting the signals [8]. It is a form of modulation whereby the nature of the modulating of the information to be transmitted changes with the quality of the transmit channel [10]. For example, in poor channel conditions (e.g., low SNR, high interference levels) the first two modulations 16-Quadrature Amplitude Modulation (QAM) and Quadrature Phase Shift Keying (QPSK) can be used while in less poor conditions, 8-PSK can be used and in the best channel conditions modulation schemes like 64 QAM, 32 APSK or 64 APSK can be used. These modulations enable more bits to be transmitted per symbol hence improving the data rate [10, 11]. In unfavourable channel state such as low SNR, high interferences, rain fade in satellite communication system, and lower level of modulation such as QPSK or Binary Phase Shift Keying (BPSK) is employed. These schemes are less sensitive to noise and interference, though the number of bits per symbol is less in comparison to previous schemes and hence a low data rate [10-13]. Table 1, shows a comparison of different modulations in Satellite Communication (SATCOM) with respect of bandwidth, its efficiency in terms of space or Bandwidth (BW), its ability to handle or tolerate BER, and the general complexity of the modulation. Amplitude Shift Keying (ASK) is considered to be unsuitable because it has nonlinear behaviour in high power amplifiers, while Minimum Shift Keying (MSK) and Gaussian Frequency Shift Keying (GFSK) has considerably moderate bandwidth efficiency as well as acceptable BER tolerance with considerable level of complexity. BER tolerance is enhanced in BPSK and QPSK while QPSK is slightly more efficient in bandwidth utilization. High order modulations such as 8PSK and APSK are most energy efficient in terms of bandwidth efficiency, however, the complexity is high specially the APSK scheme reporting highest complexity and acceptably good BER tolerance as seen in [13].

Table 3.1: Showing the Comparison of various SATCOM modulation schemes based on their BW efficiency, BER tolerance, and complexity

Modulation	**BW Efficiency**	**BER Tolerance**	**Complexity**
ASK	Not suitable due to nonlinear behavior of HPA		
MSK	Moderate	Moderate	Nominal
GFSK	Moderate	Moderate	Reasonable
BPSK	Poor	Desirable	Nominal
QPSK	Better	Desirable	Reasonable
8PSK	Best	Poor	High
APSK	Best	Reasonable	Highest

3.2 Adaptive Coding

In addition to changing the modulation scheme, the coding rate is also adapted. Forward Error Correction (FEC) codes, such as Turbo codes or Low-Density Parity-Check (LDPC) codes, are used to add redundant bits to the transmitted data to correct errors at the receiver [14]. The coding rate is adjusted to provide more error correction when the channel is poor, and less when the channel is better [15].

Higher coding rates (e.g., 7/8, meaning 7 bits of data for every 1 bit of error correction) are used in good conditions, maximizing throughput [14].

Lower coding rates (e.g., 1/2 or 1/3) are used in poor conditions, providing more redundancy for error correction, but at the cost of reduced data rate [14-16].

3.3 Adaptive Modulation and Coding Techniques

AMC techniques permit satellite communication systems to use transmission parameters adaptively according to the specific conditions of channels and interference. For example, modulation schemes and coding rates are adjustable [7]. Decrease information rate and increase error resilience leading to the maximum efficiency and minimizing the effect of interference is achieved by AMC [8]. The main problem is that the AMC scheme has to process the channel fluctuations which is faster than the end-to-end delay from the channel measurement and channel feedback [7]. The problem of understaffing is being solved through the application of the Predictive channel state information (CSI) framework which is followed by ML algorithms for accuracy. Figure 3.1 indicates system model where a satellite transponder facilitates a good number of users via a gateway. Unlike traditional algorithms, the ML algorithms show their great advantages on the complicated and changing time series by replacing the operators and weighting [7].

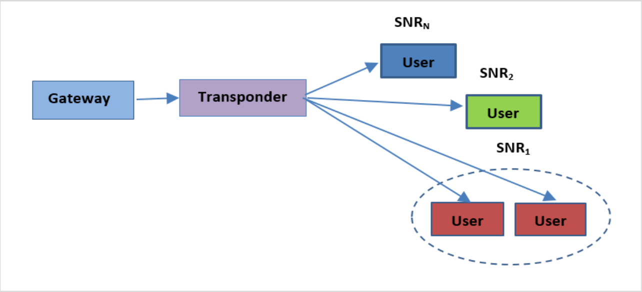


Figure 3.1: Block diagram of the system scenario, SNR

Users are being put into a few classes of a limited space ($M \leq 64$) according to their individual SNR threshold. It will be accepted that the higher class indices will be correspondent to the higher values of SNR. For each user group, the largest number of ACM modes is assigned together with the levels. The modes with higher numbers are more spectrally efficient, but the user requires a higher SNR to operate them. Data users having $j \leq i$ within a certain class are capable of managing and decoding all modes ACMj precisely [8, 4]. The gateway picks suitable ACM mode with an index $j \leq i$ for each user of class i, but may not reach the highest system capacity. However, this selection can still make the system optimized. Thus, this kind of facility offers the gateway with additional opportunities. Nevertheless, by knowing the receiving class i the system can detect and decode all possible ACMj modes with $j \leq i$. Hence, this transmission enables the system to maximize throughput by utilizing the most reliable ACM mode for each user. Indeed, the kind of feedback information we need for this optimization is not very crucial for the system just does decoding of all modes $j \leq i$ reliably [9].

3.3.1 Feedback Mechanism

For AMC to work, the receiver must constantly measure the channel quality and provide feedback to the transmitter [10]. Based on this feedback, the transmitter adjusts the modulation scheme and coding rate to match the channel conditions [11]. This feedback loop ensures that the system can adapt to real-time changes in the environment, such as fading, interference, or weather-related effects (in the case of satellite communications) [11-17].

3.3.2 Examples of AMC in Communication Systems:

- **Satellite Communications:** In satellite systems, AMC is crucial due to the variability in channel quality caused by factors like atmospheric conditions (rain fade, cloud cover), interference, and distance from the satellite. Modern standards like Digital Video Broadcasting - Satellite - Second Generation (DVB-S2) and Digital Video Broadcasting - Satellite - Second Generation Extended (DVB-S2X) implement AMC to dynamically adjust the modulation and coding schemes for video broadcasting, internet services, and data communications over satellites.
- **Wireless Networks (LTE and 5G):** In 4G LTE and 5G networks, AMC plays a vital role in maximizing the throughput for mobile users. As a user moves through different environments (e.g., urban, rural, indoors, outdoors), the channel quality changes, and AMC adjusts the modulation and coding rate to maintain optimal data transmission.

- **Wi-Fi (802.11 Standards):** Wi-Fi systems also use AMC to adjust the data rate based on the quality of the wireless link. If the link is strong, higher-order modulations like 64-QAM or 256-QAM are used, while weaker links result in the use of lower-order modulations like QPSK.

3.3.4 Benefits of AMC over traditional frequency reuse schemes

- **Enhanced spectral efficiency**: AMC takes advantage of dynamic control of modulation and coding characteristics. This ensures that spectral efficiency is optimized while achieving the highest throughput by employing the available bandwidth.
- **Improved system reliability:** Adaptive schemes and coding techniques put forward mechanisms to address link variation, fading, and interference, therefore, such link resiliency and quality of service are resulting.
- **Flexible resource allocation:** With AMC resource allocation is possible to be flexible so that the most adequate values to different traffic cases or users will be delivered.
- **Better utilization of spectrum:** AMC efficiently reuses the radio spectrum through amendment of modulation and coding schemes according to the channel state, trading-off between the throughput and coverage by means of the spectrum utilization.
- **AMC in Satellite Communications**
  In satellite systems, AMC is particularly important because of the long transmission distances and the susceptibility of the satellite link to weather conditions (e.g., rain fade), interference, and other environmental factors [18, 19]. The signal quality can degrade as a result of these issues, requiring dynamic adjustment of the modulation and coding schemes. For example: During clear weather with low interference, a satellite system may use 32-Amplitude Phase-Shift Keying (APSK) or 64-APSK to maximize data throughput. During rain fade or other adverse conditions, the system can switch to QPSK or 16-APSK with lower coding rates to maintain a reliable link, even though the data rate is reduced [19]. In standards like DVB-S2X, AMC is an integral part of the system. The standard allows for a wide range of modulation and coding schemes (from QPSK to 256-APSK), enabling efficient operation across various channel conditions [4]. This is particularly valuable for high-throughput satellite (HTS) and broadband satellite internet services, where maximizing the data rate while maintaining reliable communication is crucial.

3.4 Some Challenges of AMC

- **Complexity:** Implementing AMC requires sophisticated hardware and algorithms to continuously monitor the channel, compute the optimal modulation and coding rate, and switch between different schemes seamlessly. This increases the complexity of both the transmitter and the receiver.
- **Delay in Feedback:** AMC relies on feedback from the receiver, and any delays in this feedback can cause suboptimal modulation and coding decisions. In satellite communications, the long transmission distances can introduce delays that affect the accuracy of the channel quality measurements.
- **Interference and Fading:** In environments with fast-changing interference or fading, such as mobile networks or satellite links during weather changes, AMC must be able to adapt quickly to maintain performance. Rapid adaptation requires precise and responsive control mechanisms.

4.0 Categories Multiple Access Schemes in Satellite Communications

This section examines various multiple access schemes in satellite communications, including traditional techniques like FDMA, TDMA, and CDMA, as well as hybrid and advanced methods such as Orthogonal Frequency Division Multiple Access (OFDMA) and

Non-Orthogonal Multiple Access (NOMA). It highlights their respective strengths and limitations in managing interference, optimizing bandwidth, and adapting to traffic types in diverse SATCOM environments, while emphasizing the role of emerging technologies, which include AI and machine learning, in enhancing spectral and energy efficiency.

4.1 Primary Multiple Access Schemes

Modems using FDMA, TDMA, and CDMA for SATCOM can mitigate interference issues by utilizing separate frequency bands for uplink and downlink [3]. FDMA requires distinct frequency bands, while TDMA needs strict synchronization protocols, such as frame synchronization and carrier recovery [19]. CDMA is limited by bandwidth expansion and lower data rates [20]. Spread Spectrum Multiple Access (SSMA) with BPSK and convolutional codes can achieve near-optimal performance with low-rate FEC coding, exploiting processing gain to approach Shannon capacity [21]. Despite its effectiveness against fading, SSMA has lower bandwidth efficiency than FDMA for dedicated channels [22].

Direct Sequence Spread Spectrum (DSSS) has shown excellent performance against fading in cellular systems, particularly when using QPSK with adaptive receivers, which can improve system utilization significantly [23]. However, DSSS's spectral efficiency diminishes with longer pseudorandom sequences [24]. In contrast, OFDM can achieve higher data rates (10-15 times that of DSSS) and spectral efficiency but requires channel encoding and interleaving to reduce BER [25]. Although DSSS can operate without such measures in low SNR conditions, OFDM outperforms DSSS in spectral efficiency but has higher Peak-to-Average Power Ratio (PAPR) [26, 13]

DSSS, with multi-code spread spectrum (MCSS), has shown superior anti-jamming capabilities compared to OFDM but with bandwidth expansion costs. The Protected Tactical Waveform (PTW) for military applications combines frequency diversity and secure transmission methods, achieving low block error rates [27]. Random access protocols like ALOHA are supported by the DVB-RCS2 standard, enabling transmission without channel condition consideration, albeit requiring acknowledgment for retransmissions [28].

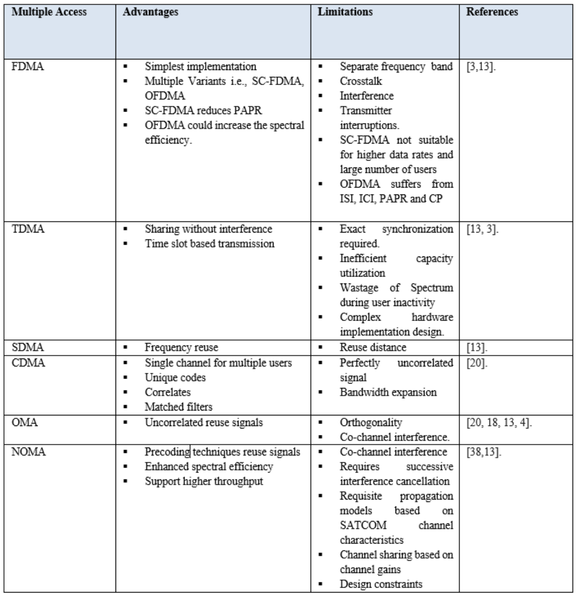
4.2 Hybrid Multiple Access Schemes

The choice between fixed and random assignment mechanisms in a network hinges on traffic type. For bursty traffic, fixed assignment can lead to inefficient spectrum use, while random access protocols are preferred despite potential packet collisions [29]. Demand Assignment Multiple Access (DAMA) struggles with sporadic IoT traffic characterized by short packets and low duty cycles [30]. Fixed assignment protocols, like OFDMA and single-carrier FDMA, allocate specific resources to users, preventing collisions during simultaneous transmissions but requiring strict synchronization to avoid co-channel interference [4]. In narrowband IoT (NB-IoT), OFDM and SC-FDMA are used for downlink and uplink communications, respectively [31]. Satellite systems manage traffic via a network control center (HUB), utilizing hybrid schemes like multi-frequency TDMA (MF-TDMA) for resource distribution [32]. Continuous carrier (CC) transmission offers dynamic adaptation to varying demands, albeit with increased complexity [33]. While MF-TDMA shows suboptimal performance in broadband satellite systems, advanced random access schemes such as enhanced spread spectrum ALOHA (E-SSA) and contention resolution diversity ALOHA (CRDSA) enhance spectral and energy efficiency through iterative successive interference cancellation, improving packet detection probabilities in satellite-IoT applications [34].

4.3 Advanced Multiple Access Schemes

Orthogonal Frequency Division Multiple Access (OFDMA) is widely used in communication standards like Digital Video Broadcasting (DVB), Digital Subscriber Line. (DSL), Wireless Local Area Network (WLAN), Wireless Metropolitan Area Network (WMAN), and Fourth Generation (4G) networks [35, 11]. It employs multiple orthogonal sub-carriers, with spacing determined by factors such as Doppler Effect and phase noise, enhancing demodulation efficiency [36]. OFDMA, also utilized in 5G systems, incorporates parameters like sub-carrier spacing and cyclic prefix (CP) length. In SATCOM, OFDMA faces multipath fading challenges, which can be mitigated by techniques like space frequency block coding (SFBC) [37]. Filtered OFDMA (F-OFDMA) reduces out-of-band emissions but may introduce inner-sub-band interferences [4]. NOMA improves spectrum utilization in 5G by allowing multiple users to share the same resources, employing techniques like successive interference cancellation (SIC) [38]. Dynamic spectrum sharing (DSS) enhances spectral coexistence across multiple systems, while hybrid satellite aerial networks (HSATN) use proactive content caching to optimize transmission delays and spectral utility [13]. Advanced beamforming techniques, such as linear beamforming and adaptive multibeam systems, help manage interference and optimize bandwidth usage in broadband SATCOM systems [39]. Table 2 compares multiple access schemes in satellite communications, including FDMA, TDMA, CDMA, OMA, and NOMA, highlighting their advantages, limitations, and key references. FDMA and TDMA offer simpler implementations but face issues with interference and synchronization, while CDMA excels in multi-user environments but requires more bandwidth. Advanced schemes like NOMA improve spectral efficiency but introduce complexity through co-channel interference and interference cancellation techniques [13, 19].

Table 4.1: Comparison of Multiple Access Schemes in Satellite Communications: Strengths and Limitations



Multiple Access	Advantages	Limitations	References
FDMA	▪ Simplest implementation ▪ Multiple Variants i.e., SC-FDMA, OFDMA ▪ SC-FDMA reduces PAPR ▪ OFDMA could increase the spectral efficiency.	▪ Separate frequency band ▪ Crosstalk ▪ Interference ▪ Transmitter interruptions. ▪ SC-FDMA not suitable for higher data rates and large number of users ▪ OFDMA suffers from ISI, ICI, PAPR and CP	[3,13].
TDMA	▪ Sharing without interference ▪ Time slot based transmission	▪ Exact synchronization required. ▪ Inefficient capacity utilization ▪ Wastage of Spectrum during user inactivity ▪ Complex hardware implementation design.	[13, 3].
SDMA	▪ Frequency reuse	▪ Reuse distance	[13].
CDMA	▪ Single channel for multiple users ▪ Unique codes ▪ Correlates ▪ Matched filters	▪ Perfectly uncorrelated signal ▪ Bandwidth expansion	[20].
OMA	▪ Uncorrelated reuse signals	▪ Orthogonality ▪ Co-channel interference.	[20, 18, 13, 4].
NOMA	▪ Precoding techniques reuse signals ▪ Enhanced spectral efficiency ▪ Support higher throughput	▪ Co-channel interference ▪ Requires successive interference cancellation ▪ Requisite propagation models based on SATCOM channel characteristics ▪ Channel sharing based on channel gains ▪ Design constraints	[38,13].

5.0 Findings

Advanced AMC has adaptability in characteristics of the transmission such as SNR and BER thresholds. Factors incorporating the use of modulation levels such as, QPSK, 16-QAM and coding rates help in establishing modulation and coding schemes to adapt to the channel conditions in real time. For instance, channel with greater SNR enables the use of higher order modulation thus promoting throughput and on the other hand; lesser SNR promotes the use of more reliable coding schemes in terms of link reliability. As compared with other schemes for frequency reuse like FDMA, TDMA and CDMA, AMC can use the transmission parameters as per the changing conditions of the channel in satellite communication. This adaptability enhances spectral efficiency and system reliability, especially in environments with change in interference and signal quality. For example, As FDMA allocates fixed frequency bands, TDMA relies on time slots. AMC adapts dynamically, maximizing spectrum usage and increasing spectral efficiency by 30-50% under optimal conditions [40]. Recent studies show that AI and ML tools can achieve even higher performance of AMC systems. For instance, deep learning (DL) and DRL approaches have been employed with AMC for LEO satellite networks to maximize satellite-to-ground communication in changing weather conditions. These techniques dynamically adjust coding schemes based on current weather and location data, enhancing throughput while addressing challenges like channel fading and signal dynamics [41]. Moreover, research on deep-learning-based AMC for LEO satellite-terrestrial networks demonstrates that data-driven models can outperform traditional AMC approaches in throughput and reliability. These models effectively address unpredictable changes in communication channels, improving system performance in innovative satellite settings [42]. AMC also plays a crucial importance in ubiquitous networking and computing for satellite communication systems. Emerging trends such as multiple-input multiple-output (MIMO) technologies are explored, which introduce AMC's potential to achieve efficiency in highly dynamic satellite communication contexts [43]. Applications in LEO, Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) systems further illustrate AMC's versatility, with LEO systems benefiting most due to their rapidly changing channel characteristics.

While AMC provides substantial importance, including improved spectral efficiency and system adaptability, it introduces the problem of complexity. This includes the need for advanced hardware, sophisticated algorithms, and effective feedback systems. These aspects are particularly critical in mobile networks or satellite links influenced by weather conditions, where flexibility and adaptability are key to maintaining reliable communication.

Feedback delays also represent a significant challenge for AMC in dynamic environments, particularly in high speed LEO satellite systems. These delays, caused by the time required to measure channel conditions and transmit feedback, can degrade system performance in fast-changing conditions. Feedback loop latency of even a few milliseconds in LEO systems can lead to outdated modulation and coding decisions, reducing link reliability.

Potential solutions to mitigate these delays include the use of predictive algorithms and hybrid approaches. Predictive algorithms leverage ML models to anticipate channel conditions based on historical data, reducing reliance on real-time feedback. Hybrid methods combine AMC with robust baseline coding schemes to ensure reliable communication even during feedback disruptions. Such techniques are essential for ensuring AMC's effectiveness in highly dynamic satellite environments.

6.0 Conclusion

The comparison between traditional frequency reuse schemes which includes; FDMA, TDMA, and CDMA, and AMC reveals a clear transition in satellite communication toward more dynamic and efficient systems. In conventional methods, while fundamental are limited in their ability to address the demands of modern SATCOM environments which are characterized by fluctuating traffic demands and harsh atmospheric conditions. AMC with its potential of choosing appropriate modulation and coding automatically depending on the current channel state could be considered to offers a robust alternative in terms of improved spectral efficiency, reliability and interference management. Recent advances in AI and machine learning has expanded, complementing AMC’s capabilities, enabling predictive and adaptive techniques that address challenges like channel fading and rapidly varying signal conditions.

These findings highlight AMC's adaptability in characteristics of the transmission such as SNR and BER thresholds. Factors incorporating the use of modulation levels such as QPSK, 16-QAM, and coding rates help establish modulation and coding schemes to adapt to the channel conditions in real time. For instance, channels with greater SNR enable the use of higher-order modulation, thus promoting throughput, while lesser SNR promotes the use of more reliable coding schemes, enhancing link reliability. As compared with schemes like FDMA, TDMA, and CDMA, AMC's dynamic adaptation maximizes spectrum usage and increases spectral efficiency by 30-50% under optimal conditions.

Recent advances in AI and machine learning have expanded AMC’s capabilities, enabling predictive and adaptive techniques to address challenges like channel fading and rapidly varying signal conditions. For example, DL and DRL have been applied in conjunction with AMC, in LEO satellite networks, to modify coding models depending on weather and location information, to achieve higher throughput, and to deal with such issues as channel variability. In LEO satellite-terrestrial networks, data-driven AMC models also show promising results in boosting the throughput and reliability and contribute to the growing importance of AMC in innovative satellite settings.

These findings underscore the crucial importance of AMC in shaping the future of SATCOM systems and its potential to cater to increasing data demands, improve spectrum management, and support communication needs in challenging environments. This stresses the need to incorporate evolving DL and DRL technologies into the future of satellite communication, as AMC continues to play a critical role in modernized telecommunication networks.

References

1. T. Leng, Y. Wang, D. Hu, G. Cui and W. Wang, "User-level scheduling and resource allocation for multi-beam satellite systems with full frequency reuse," in *China Communications*, vol. 19, no. 6, pp. 179-192, June 2022, doi: 10.23919/JCC.2022.06.014.
2. Hao, C., Wan, X., Feng, D., Feng, Z., & Xia, X. G. (2021). Satellite-based radio spectrum monitoring: Architecture, applications, and challenges. *IEEE Network*, *35*(4), 20-27.
3. Ilcev, S. D. (2020). Analyses of Frequency Division Multiple Access (FDMA) Schemes for Global Mobile Satellite Communications (GMSC). *TransNav, International Journal on Marine Navigation and Safety od Sea Transportation*, *14*(4), 811-819.
4. Kumar, A., & Kumar, K. (2020). Multiple access schemes for cognitive radio networks: A survey. *Physical Communication*, *38*, 100953.
5. Yan, Y., Xu, H., Zhang, N., Han, G., & Liu, M. (2021). Dynamic divide grouping non-orthogonal multiple access in terrestrial-satellite integrated network. *Sensors*, *21*(18), 6199.
6. Tang, J., Bian, D., Li, G., Hu, J., & Cheng, J. (2021). Resource allocation for LEO beam-hopping satellites in a spectrum sharing scenario. *IEEE Access*, *9*, 56468-56478.
7. X. Wang, H. Li and Q. Wu, "Optimizing Adaptive Coding and Modulation for Satellite Network with ML-based CSI Prediction," *2019 IEEE Wireless Communications and Networking Conference (WCNC)*, Marrakesh, Morocco, 2019, pp. 1-6, doi: 10.1109/WCNC.2019.8885616.
8. Kharchenko, V., Wang, B., Grekhov, A., & Leschenko, A. (2016). Modelling the satellite communication links with orthogonal frequency-division multiplexing. *Transport*, *31*(1), 22-28.
9. Kayhan, F., and Montorsi, G. (2016) Code design for adaptive coding and modulation indicator in broadcast systems. *Int. J. Satell. Commun. Network.*, 34: 771–785. doi: 10.1002/sat.1131.
10. Singya, P. K., Shaik, P., Kumar, N., Bhatia, V., & Alouini, M. S. (2021). A survey on higher-order QAM constellations: Technical challenges, recent advances, and future trends. *IEEE Open Journal of the Communications Society*, *2*, 617-655.
11. Henarejos, P., & Pérez-Neira, A. I. (2015). Dual polarized modulation and reception for next generation mobile satellite communications. *IEEE Transactions on Communications*, *63*(10), 3803-3812.
12. Huang, J., Su, Y., Liu, W., & Wang, F. (2016). Adaptive modulation and coding techniques for global navigation satellite system inter-satellite communication based on the channel condition. *Iet Communications*, *10*(16), 2091-2095.
13. M. N. Danish and S. A. Pasha, "Satellite communication: State-of-theart and future challenges,"accessed: 2023 10 11. [Online]. Available: https://www.researchgate.net/profile/Muhammad-

Danish-19/publicatio n/371503006 Satellite Communication State-of-the-Art and Future Challenges/links/ https://www.researchgate.net/publication/371503006_Satellite_Communication_State-of-the-Art_and_Future_Challenges.

14. Fanari, L., Iradier, E., Bilbao, I., Cabrera, R., Montalban, J., Angueira, P., ... & Val, I. (2022). A survey on FEC techniques for industrial wireless communications. *IEEE Open Journal of the Industrial Electronics Society*, *3*, 674-699.
15. Srivastava, S., Banerjee, A., & Gupta, A. K. (2023, December). On Performance Evaluation of Channel Codes over Satellite Channels. In *2023 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)* (pp. 379-384). IEEE.
16. Li, A., Spano, D., Krivochiza, J., Domouchtsidis, S., Tsinos, C. G., Masouros, C., ... & Ottersten, B. (2020). A tutorial on interference exploitation via symbol-level precoding: Overview, state-of-the-art and future directions. *IEEE Communications Surveys & Tutorials*, *22*(2), 796-839.
17. Kebede, T., Wondie, Y., Steinbrunn, J., Kassa, H. B., & Kornegay, K. T. (2022). Multi-carrier waveforms and multiple access strategies in wireless networks: performance, applications, and challenges. *IEEE Access*, *10*, 21120-21140.
18. Chan, S., Zhang, M., Oh, D., & Kim, S. (2018, October). Rateless codes for satellite systems over rain fading channels. In *36th International Communications Satellite Systems Conference (ICSSC 2018)* (pp. 1-6). IET.
19. Xue, R., Zhao, M., & Tang, H. (2020). Information transmission schemes based on adaptive coded modulation for UAV surveillance systems with satellite relays. *IEEE Access*, *8*, 191355-191364.
20. Touati, S., Sammouda, R. and Alhussein, M., 2024. CDMA extension using STARRIS. *International Journal of Ad Hoc and Ubiquitous Computing*, *47*(1), pp.22-27.
21. Delwar TS, Siddique A, Biswal MR, Rashed AN, Jana A, Ryu JY. Novel multi-user MC-CSK modulation technique in visible light communication. Optical and Quantum Electronics. 2021 Apr;53:1-6.
22. Cai, J. (2002). *Robust error control and optimal bit allocation for image and video transmission over wireless channels*. University of Missouri-Columbia.
23. Satyanarayana, B. V. V., Teja, N. S. S., Pavan, M., Smrini, K., Kumar, G. P., & Budumuru, P. R. (2024, February). FPGA Implementation of Correlator for Direct Sequence Spread Spectrum (DSSS) Systems. In *2024 International Conference on Integrated Circuits and Communication Systems (ICICACS)* (pp. 1-8). IEEE.
24. Lu, Q., He, F., Wang, Z., Ma, Y., Yang, Z., Li, Y., ... & Li, W. (2024). Performance Analysis for DSSS with Short Period Sequences Encountering Broadband Interference. *IEEE Transactions on Vehicular Technology*.
25. Li, Q., Wen, M., Basar, E., & Chen, F. (2018). Index modulated OFDM spread spectrum. *IEEE Transactions on wireless communications*, *17*(4), 2360-2374.
26. Liu, H., Jiang, Y., & Liang, X. (2021, December). A joint PAPR suppression scheme of DSSS-GFDM system using DFT precoding and clipping for satellite communications. In *2021 7th International Conference on Computer and Communications (ICCC)* (pp. 1976-1984). IEEE.
27. Nguyen, L. K., Wells, R. B., Nguyen, D. H., & Tran, N. H. (2017, October). Outage probability analysis of the Protected Tactical Waveform (PTW) on the return link. In *MILCOM 2017-2017 IEEE Military Communications Conference (MILCOM)* (pp. 894-899). IEEE.
28. Munari, A. (2021). Modern random access: An age of information perspective on irregular repetition slotted ALOHA. *IEEE Transactions on Communications*, *69*(6), 3572-3585.

29. Hapanchak, V. S. (2024). Integration of different radio access technologies for vehicular connectivity.
30. Sandhu, M. M., Khalifa, S., Portmann, M., & Jurdak, R. (2023). *Self-Powered Internet of Things: How Energy Harvesters Can Enable Energy-Positive Sensing, Processing, and Communication*. Springer Nature.
31. Feltrin, L., Tsoukaneri, G., Condoluci, M., Buratti, C., Mahmoodi, T., Dohler, M., & Verdone, R. (2019). Narrowband IoT: A survey on downlink and uplink perspectives. *IEEE Wireless Communications*, *26*(1), 78-86.
32. Kodheli, O., Lagunas, E., Maturo, N., Sharma, S. K., Shankar, B., Montoya, J. F. M., ... & Goussetis, G. (2020). Satellite communications in the new space era: A survey and future challenges. *IEEE Communications Surveys & Tutorials*, *23*(1), 70-109.
33. Hanzo, L., Webb, W. T., & Keller, T. (2000). *Single-and multi-carrier quadrature amplitude modulation: principles and applications for personal communications, WATM and broadcasting: 2nd*. IEEE Press-John Wiley.
34. De Gaudenzi, R., del Río Herrero, O., Cioni, S., & Mengali, A. (2019). Random access versus multiple access. *Multiple Access Techniques for 5G Wireless Networks and Beyond*, 535-584.
35. Logvinov, V. V., & Smolskiy, S. M. (2022). Systems and networks of wireless communication. In *Radio Receivers for Systems of Fixed and Mobile Communications* (pp. 51-119). Cham: Springer International Publishing.
36. Yiqi, B., & Chuanlin, H. (2022). Analysis of Doppler and multipath on orthogonal chirp division multiplexing in shallow water acoustic channel. *IEEE Access*, *10*, 95928-95935.
37. Zhang, Y., Wang, B., Li, X., Liu, N., Ji, W., & Li, X. (2020). Multiple carrier frequency offset compensation for cooperative HAPS IoT systems. *EURASIP Journal on Wireless Communications and Networking*, *2020*, 1-17.
38. Iswarya, N., & Jayashree, L. S. (2021). A survey on successive interference cancellation schemes in non-orthogonal multiple access for future radio access. *Wireless Personal Communications*, *120*(2), 1057-1078.
39. Rao, L., Pant, M., Malviya, L., Parmar, A., & Charhate, S. V. (2021). 5G beamforming techniques for the coverage of intended directions in modern wireless communication: in-depth review. *International Journal of Microwave and Wireless Technologies*, *13*(10), 1039-1062.
40. Shah-Mohammadi F, Enaami HH, Kwasinski A. Neural network cognitive engine for autonomous and distributed underlay dynamic spectrum access. IEEE Open Journal of the Communications Society. 2021 Mar 30;2:719-37.
41. E. Lanfer, D. Laniewski, D. Otten, and N. Aschenbruck, "Weather-Based Link Prediction for LEO-Satellite Networks using the WetLinks Dataset," 2024 IFIP Networking Conference (IFIP Networking), Thessaloniki, Greece, 2024, pp. 586-588, doi:10.23919/IFIPNetworking62109.2024.10619789.
42. Y. Xia et al., "Leveraging Deep-Learning for Adaptive Coding and Modulation for LEO Satellite-Terrestrial Networks," 2024 IEEE/CIC International Conference on Communications in China (ICCC), Hangzhou, China, 2024, pp. 774-779, doi:10.1109/ICCC62479.2024.10681710.