

ACT-SAT1

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Abstract

Adaptive communication technologies Satellite (ACT-Sat1), is a mission that will utilize a Blank-Slate AI with the goal of maximizing the communications system on board a CubeSat. CubeSat communication systems have to deal with a multitude of restrictions including strict power, bandwidth, and link budget constraints. Right now, systems are set to deal with an ideal, unchanging situation. This is where AI comes into play; by training a blank-slate AI to adapt on-board systems to maximize communication efficiency. ACT-Sat1 will change the specific restrictions in place for a communication system to determine the most efficient settings at different points in orbit. This system will lead to increased downlink efficiency, reduced power waste, and improved autonomy and operational lifespan. The benefit of maximizing downlink efficiency is a reduced operational cost for groundstations due to less total passes. This kind of system could reduce the total operational cost of a CubeSat by around 20-40%. If this mission proves to be successful with the communication system, it could open the door to maximizing other systems on board a CubeSat like EPS, thermal management, and ADCS. In order to train the AI model, it will be given a set of radio telemetry data as well as a description of its effects on the CubeSat. These will include SNR, BER, RSSI, etc. The AI will also be given a list of values it can change during different scenarios such as transmitter power, bandwidth, and SDR gain settings. The AI will be given rewards for certain actions to encourage effective behavior. The system will then be put through a simulator where it will encounter different real-life scenarios and learn what improves the communications. The AI will be housed in a Raspberry Pi Compute Module 4 (CM4) due to its compact build and ideal power usage at .5 to 1 watt. Even if ideal conditions are not met in space this model will peak at 5 watts. Due to the fact that the AI will only be running during downlink this is a very manageable wattage to meet. The CM4 would then be connected to an OBC, but since they are separate boards, if the AI stops working, the satellite can still function which means we can still deorbit the CubeSat safely. Additionally, if the AI stops responding the OBC can acknowledge that and power cycle the AI to getting back up and running.

Keywords: *CubeSat communications, artificial intelligence, downlink efficiency, autonomous satellite systems, CubeSat cost reduction.*

1. What is the Wolfpack?

The WolfPack CubeSat Development Team (WCDT) is a group of pre-college students who lead in researching, designing, and creating CubeSats. The team focuses on aerospace and provides students with an option of three possible pathways: engineering, public policy, and entrepreneurship. The WCDT has successfully launched multiple missions, including WeissSat-1 (2018), CapSat-1 (2022), and FlipSat (2025). The WCDT has allowed for an early pipeline directly into the aerospace workforce as it allows students to gain real-world experience prior to graduating high school. In the engineering division, students conduct extensive research to propose CubeSat ideas for future missions.

2. CubeSat communications

The communication subsystem serves as the most influential component of the CubeSat. In order to ensure mission success, being able to reliably transmit telemetry, as well as updates, to the satellite's payload is critical. These systems constitute the majority of operational costs because of "passes" (paying groundstations to accept satellite data). Current limitations CubeSats face include frequency challenges, scheduling conflicts, and orbital conditions. This comes as a result of the inability for the system to adapt in-flight.

2.1. Current state of CubeSat communications

CubeSat communication is fundamentally a trade between flexibility, power efficiency, and mission specificity. Current systems fall into four different design categories: custom software-defined radios (SDRs), commercial SDRs, custom hardware radios, and commercial off-the-shelf (COTS) hardware systems; each with their own strengths and weaknesses (Zeedan & Khattab, 2023). Custom SDRs have high flexibility and field-programmable gate array (FPGA) dominated signal processing chains. However, these systems deal with high power consumption as data rate increases. Commercial SDRs are optimal for limited development time, but their resource-inefficiency and often over-sized memory makes them better suited for technology demonstrations and payload-driven missions. In regards to hardware systems, custom allows for the greatest power efficiency but sacrifices reconfigurability and adaptivity. By contrast, commercial hardware enables extreme data rates at the cost of major power consumption; these are often the choice for 3U-6U platforms with aggressive power budgets.

Across nearly all high-performance CubeSat systems, FPGA-centric baseband architectures dominate with their parallelism and efficiency. According to Zeedan and Khattab (2023), FPGAs handle forward error correction (FEC) processing, modulation, pulse shaping, Doppler correction, and framing, while CPU or ARM cores manage control logic and data flow. Currently, low-density parity-check (LDPC) decoding dominates power and computation, especially as iteration count increases.

Performance is also strongly influenced by the frequency the radio uses (Zeedan & Khattab, 2023). VHF/UHF systems favor low power and long access times at the cost of data rate, while S-band offers a balanced choice for many CubeSats. X-band and Ka-band radios offer exponentially higher throughput but introduce higher power costs, atmospheric issues, and pointing challenges.

Adaptability in communication has become the norm for CubeSats at large. Adaptive communication and modulation increase the efficiency for systems under variable signal-to-noise ratio (SNR). Shutdown and standby cycling significantly reduce power draw and is often more impactful than optimizing modulation alone.

Although adaptive systems have been beneficial, in practice, power consumption scales superlinearly with data rate due to FEC complexity, radio frequency (RF) power amplifier efficiency, and multi-channel operations. A higher demand for systems with increasingly large data rates have begun to consume increasingly large portions of CubeSat power budgets.

2.2. Problems and limitations of CubeSat communications

The most obvious limitation for CubeSat communication systems is their finite size. The small form factor equals fewer transceivers and antennas; power limits mean shorter range and contact times; and limited storage leads to forced tradeoffs between buffering and downlink (Saeed et al., 2020).

On the more technical side, restrictions with bandwidth and data rates also cause many issues. Narrower bandwidths decrease data rates, resulting in less data travelling from the satellite to the ground. Delays in communications arise from latency issues, and heavy traffic with simultaneous connections degrades the overall performance of the systems. These issues not only slow down the communications, but severely limit their efficiency.

Physics-driven issues, such as orbital dynamics and the doppler effect, also mitigate the effectiveness of communication systems. Rapid Doppler frequency shifts in low-Earth orbit (LEO) lead to reduced communication session durations. This becomes especially problematic at low altitudes or fast-moving orbits; not unlike those which CubeSats tend to be in most cases. According to Saeed et al, (2020), these shifts significantly impact IoT-style protocols such as LoRa and fixed multiple-access schemes, which assume narrowband operation, stable carrier frequencies, and loosely synchronized devices. Rapid frequency changes and time variations degrade demodulation performance, increase packet loss, and undermine scheduling mechanisms that are designed for mostly unchanging environments. Although these methods show good results on Earth, their viability breaks down beyond the terrestrial environment.

Beyond the RF link, the communication systems still deal with many problems; a majority of which include scheduling and resource conflicts. With a limited amount of transceivers, systems must prioritize tasks and data routing. Power limitations caused by solar restraints drive scheduling since transmission power often exceeds what the satellite can contain continuously, therefore, downlinks must occur at times when the satellite is charging. While this is happening, multiple satellites are also arranging communication times, which requires complex routing, leading to more issues.

Additionally, the protocols and networks themselves are inherently flawed in various ways. Modern networks are often hardware-dependent, which means low flexibility. While software-defined networking (SDN) systems appear as attractive solutions, they are technically challenging and hard to maintain on resource-limited CubeSats.

These constraints are further amplified by environmental disturbances and the complexities of multi-satellite communication networks. Being in a space-environment introduces signal attenuation, weather effects, and radiation hazards; adding more variables to take into consideration. Dynamic networks that include satellites in LEO and GEO, HAPs, and UAVs lead to strain that make link connections harder to maintain (Saeed et al., 2020).

3. Artificial intelligence replacement

3.1. How AI will improve the system

With the recent leaps in artificial intelligence (AI), combined with the various issues CubeSat communications have to deal with, it is inevitable the two would work together in order to create a more efficient system. With a trained AI, problems such as low SNR, Doppler shifts, limited power and bandwidth, and short communication windows could be dealt with in real-time on the satellite. With the fixed-rule systems right now, satellites struggle in dynamic environments like LEO and AI is the natural solution.

A particular issue CubeSats face where AI would strive is low SNR. According to Manikandan, Babu, Ganesh, and Sanjay (2025), an AI system would be able to improve the effective SNR through noise pattern recognition and subsequent suppression of such interference. Traditional filters are based on assumed noise models with fixed coefficients and cut-off frequencies; they are usually designed for average or worst-case scenarios. These systems perform especially poorly when noise statistics change, the interference is non-stationary, or when the SNR varies rapidly during a pass. With an AI, the system could learn noise and interference characteristics through data and adapt over time.

To maximize data delivery and minimize errors, the communication system must adapt instantly to time-varying channels. AI fulfills this role by dynamically selecting modulation, coding, and data rates; this improves performance and efficiency far beyond current systems. The AI could choose from a range of modulation options (e.g., BPSK, QPSK, 16-QAM, 64-QAM) based on predicted channel quality; using high-order modulation when SNR is high to maximize throughput and low-order modulation when SNR is low to ensure link reliability (Manikandan et al. 2025). Simultaneously, the AI could dynamically choose FEC coding rates to balance throughput and reliability. Similar to the modulation options, higher coding rate could be used when the channel is clear and lower coding rates when the network is noisy. Over the course of the mission, the AI could track fast variations caused by orbital movement and relative velocities. This would allow the AI to more accurately predict channel trends to further reduce interruptions. This all results in a higher bandwidth utilization and more data per pass.

Additionally, an AI system could take more variables into account versus a traditional communications system. The AI could consider power levels, solar availability, and thermal limits. This enhances the system by taking into account certain CubeSat constraints that must be faced. Using this telemetry, the scheduling of the CubeSat will be determined by the AI. Transmissions would only occur when the link quality justifies its own power use, delaying non-critical data. Through autonomous scheduling, the satellite would be less reliant upon ground intervention and would react faster than human-in-the-loop systems.

In order to reach all these improvements, the AI must meet a multitude of requirements. In order to adapt and change quickly, the AI must be capable of real-time processing all the telemetry it is sent. The AI must also be radiation tolerant and have a low-power consumption so as not to limit the ability of the CubeSat to perform its mission. In order to align with popular traditional systems, the AI must be based on an FPGA-centric architecture with onboard inference and easy system integration.

3.2. How the AI will work

The AI will be integrated onto the system by running directly on the FPGA fabric, essentially enhancing the “brain” of the communications. The benefits of this are a lower latency, an energy-efficient computation, and being physically closer to the radio itself. Additionally, this will reduce the reliance on slower general-processors, enabling real-time signal processing. With the importance of fast reactions and adjustments for the AI to be deemed beneficial, this integration style is most advantageous for the system (Liu, Liu, Shi, & Hao, 2025).

Certain telemetry will be sent to the AI system in order to clearly and accurately represent the current environment it is in, also called “channel quality measurements” (Manikandan et al. 2025). This is especially important for decision-making, so the AI can compare the data to pre-trained scenarios. These metrics will most-likely include SNR, bit error rate (BER), Doppler frequency offset, received signal-strength indicator (RSSI), etc. This data shows how strong the incoming signal is, how clean it is relative to noise, and the actual effect on data integrity. The AI will be able to take all these metrics into account and select an optimal modulation scheme, coding rate, and data rate. System resources like power

level and battery state will also be taken into consideration, along with environmental variables such as thermal and radiation readings. These inputs allow the AI to accurately predict the optimized communication telemetry to use for the next pass.

Throughout communication passes, the AI will continuously evaluate link conditions. Changes in transmit power, modulation and coding schemes, data rate, and packet scheduling will all be controlled by the AI. This constant loop allows for autonomous adaptations without ground intervention. With the constantly changing environment that is LEO, the importance of dynamic link optimization cannot be stressed enough, especially when it comes to making rapid channel changes because of Doppler effects and fluctuating power (Liu et al., 2025). This system will allow for improved throughput, lower error rates, and better spectral utilization.

3.3. How the AI will be trained

Long before the satellite is launched, the AI will go through long and rigorous training. The AI will be trained in a computer-simulated space environment (Liu et al., 2025), which will include Doppler shifts, noise, interference, power fluctuations, and orbital dynamics. The AI will experience various scenarios with different data in order to recognize patterns and common solutions. The AI's response to scenarios will be compared to historical CubSat mission data to teach the system what an "exceptional" response would look like. Based on link conditions, the AI will learn to select optimal modulation, coding, and power control. Once a high-level of confidence is established in the AI, it will undergo hardware-in-the-loop testing to simulate worst-case scenarios, ensuring it meets timing, data rate, and power constraints. This establishes a robust baseline for autonomous on-orbit operations and validates safe behavior under extreme conditions.

Once in orbit, the AI will experience a limited online learning or parameter updates to adjust to real-world conditions not captured in the simulations, such as unexpected interference and orbital variations. These updates will be carefully constrained in order to avoid system instability or excessive power consumption. Training will also address radiation effects with redundancy and error detection mechanisms to ensure reliable decisions.

4. System architecture

4.1. Hardware implementation

ACT-Sat1 will house one primary on board computer (OBC) and a secondary AI processing board. The primary board will be an EnduroSat OBC with GNSS which will send and receive signals from the secondary board, and send the commands to the communication system. This board was chosen due to its extensive flight heritage and tolerance to factors such as radiation and power survival. The secondary processing board will be a CM4 raspberry pie which has high computation abilities while being a low power board. It also is easy to power cycle with EnduroSat, mitigating risks like BitFlips and power outages. This allows the heavy computations from the AI to be solely done in the secondary board and the function of the satellite subsystems to be taken care of by the main OBC.

4.2. Communication subsystems

This satellite would employ a UHF/VHF communication system due to its easy integration into smaller satellites like a 1U, lower cost because of shorter passes, and lower transmit power. This system would be directly connected to the OBC which will receive signals from the CM4 (secondary processor) to alter bandwidth requirements inflight. This will allow for the satellite to operate within the amateur radio frequency using VHF for uplink and UHF for downlink.

4.3. Structural design

ACT-Sat 1 will be a 1U CubeSat form factor as a result of its lower cost, lower risk, and prioritization of intelligence rather than a power intensive payload. A 1U CubeSat can often cost about 2 to 3 times cheaper than a 3U, and about 5 to 8 times cheaper than a 6U. This makes a 1U ideal as it can act as a test for validating AI's use in space without the risk. If the 1U works the mission can be scaled up to 3U or 6U for a more detailed experiment.

The Central Electrical Power System (EPS) will regulate and distribute power. Our model will keep the OBC running at all times and the secondary board with the AI will be turned on during downlink processes. The focus of power will be into the OBC and communication system with the secondary board being the lower priority. This will allow us to keep the mission alive if the AI shuts off and be able to deorbit safely. Another benefit to having the OBC as the top priority of the EPS is that they can work together to power cycle the CM4 if anything goes wrong. The model of duty cycling will reduce power demand, enabling the mission to be more efficient and have a lower cost.

5. Risks and mitigations

5.1. Environment and hardware risks

Operation in Low Earth Orbit (LEO) exposes our satellite to radiation from the sun. This can severely affect the AI through BitFlips which is when a 0 turns into a 1 or a 1 turns into a 0. According to Granat, Wagstaff, Bornstein, Tang, and Turmon (2009), Radiation can cause a variety of errors in memory, including flipped bits, stuck bits, and damaged components. While one Bitflip can be manageable, multiple can cause complete destruction of the AI software. To mitigate this we will use error correcting code (ECC) and supervisory control by the OBC to alert of any faults in the code without compromising the entirety of the spacecraft. AI, by nature of their application, are placed close to the data source and cannot be ideally protected from environmental factors, for instance, the radiation at space and terrestrial levels (Rajappa, 2025).

Thermal cycling throughout orbit also poses a severe threat to the integrity of the spacecraft. Conservative duty cycling of the AI will limit heat accumulation on sensitive components like the CM4 board and main on-board computer.

5.2. Regulatory and operational constraints

Communication activities on ACT-Sat1 have to be within all FCC regulatory limits. The adaptive communication system must operate within these regulations. The AI cannot independently select frequency, bandwidth, and transmit power, it must all be legal under FCC regulation.

By optimizing communication settings during active contact with ground stations, the mission aims to maximize throughput while minimizing ground station passes.

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