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Mokshith Sharma T P

mokshithsharma1411@gmail.com

Nitte Meenakshi Institute of Technology https://orcid.org/0009-0001-0499-6357

Research Article

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Mokshith Sharma T P

Department of Aeronautical Engineering

Nitte Meenakshi Institute of Technology, Bangalore, India

Email: mokshithsharma1411@gmail.com

Abstract

This study outlines a practical design for an energy-conscious S-band communication system meant for a 6U CubeSat measuring 30 by 20 by 10 centimeters. Instead of building only physical prototypes, the approach uses a digital twin method to test designs early. That way, key decisions get checked well before finalizing any actual hardware. The full setup covers everything from radio frequency components to data framing aligned with CCSDS standards. Error protection during transmission is included too. Processing happens through flexible electronics - software-driven logic on FPGA chips handles the signal tasks

A chip plus two antennas set up for stable signal during spin. Testing three ways to send data: one basic radio path, another smarter S-band method adjusting speed using phase shifts while switching between patches, also a bigger unfolding dish idea for more volume. With clear rules like orbit height at 500 km, Earth station size near 1.2 meters, losses guessed on the safe side, it calculates how much power each connection needs, checks flow rates when satellites rise above horizon, probes error risks tied to different wave patterns used. Findings tilt toward smart QPSK with flexible code strength paired with twin surface antennas - handles dropouts well, saves battery life per useful chunk sent, stays manageable to build, fits tight spaces too. Mirror-world technique ties math models of signals, satellite paths overhead, juice supply timing, heat limits from active periods into a cycle that runs again and again, testing contact success ahead of flight under varied operational scenes.

The proposed architecture demonstrates a practical and energy-efficient communication framework suitable for 6U CubeSat missions under constrained orbital and power conditions. - a way to piece together small systems reliably. Testing fits within tight constraints typical of tiny satellites. Results can be checked again by others. This method holds up even when tools and time are scarce.

Keywords: CubeSat; S-band communications; CCSDS; link budget; virtual twin; energy-aware downlink; SDR; FPGA; digital twin validation

1. Introduction

Now picture tiny satellites once used just for classroom projects now pulling real duties in orbit. Yet getting data home stays tough since they juggle tight room for antennas, weak power supply, tight size rules, plus must stay linked even when tumbling randomly. Take the 6U kind - it gives space for useful gear, though radios still fight for juice, cooling, and structure room. Here’s where S-band stands out. Not too slow like old-school UHF signals, not as fussy as X-band that demands perfect aim and complex setup.

This work treats the communications part not as just a radio box but as part of the full mission setup. Instead of asking if parts fit, it asks: can we build, test, and check an energy-conscious S-band layout inside a digital version of a 6U CubeSat long before launching hardware? Problems in small satellite links usually do not come from one broken piece; they rise when signal shape, pointing errors, code settings, on-off timing, heat margins, and station location collide. So, any smart approach needs to blend radio behavior with battery load and temperature logic, checking performance over many orbits instead of one ideal moment.

The contribution of the paper is fourfold. First, it proposes a complete S-band subsystem architecture that fits within 6U constraints and supports adaptive mission modes. Second, it derives a transparent analytical model for the downlink and uplink link budgets, power budget, and duty-cycle behavior under explicit assumptions.

Starting fresh, this method ties an analytical setup to live simulation through a digital clone system - linking altitude, reach, and energy needs into one view. Next up, three design versions get weighed against each other, revealing why the pick made fits best inside tight limits of a 6U CubeSat flying low around Earth. What matters here isn't flashy results but clear steps anyone could follow again.

Here comes how the rest unfolds. After that, part two looks at past work on CubeSat links, antennas, codes, along with digital twins. What drives the setup shows up next - Section Three lays out needs plus the working guesses behind them. From there, a design appears in Section Four. Math steps forward when Section Five builds formulas for signal strength and energy use. Then again, Section Six walks through how the virtual copy operates. Results pop up once simulations run, explained fully in Section Seven. Choices get measured against each other by Section Eight. Even so, weak spots remain, called out plainly in Section Nine alongside what might come later. Last of all, Section Ten wraps things up without extra claims.

2. Related Work

How CubeSats talk to Earth depends heavily on their fixed shape plus strict size rules set by launch containers. Though built in units from 1U to 12U using standards like Revision 14.1, they still favor low cost over power. Agencies such as ESA and NASA point out speed and price often limit what these tiny craft can do. That matters here because six-unit models give some room - just not enough to ignore old limits. Big antennas? Limited space. Large batteries? Hard to fit. Heat control? Still tight. Even with more volume than smaller versions, basic hurdles stay firmly in place.

One step below, CCSDS sets the baseline when it comes to linking systems that send and receive data across space missions. Framing, along with how signals are encoded for downlink traffic, falls under the TM Sync and Channel Coding rulebook. For uplinks, a separate but similar set of rules - TC Sync and Channel Coding - takes charge. Packets carrying mission information stay independent from hardware thanks to Space Packet Protocol, acting like a bridge between data and transmission gear [4–6]. That big-picture view? It lives in the CCSDS summary paper, which maps out today's network approaches while showing smaller satellites can blend custom radio setups with standard packet formats - all while staying compatible [7].

CubeSat research often shows S-band stepping in once UHF hits its limit for dependable data flow - yet before X-band's strict aiming and size needs make sense. Looking at NASA's work on small satellite communications, software-defined radios for S-band, and ground networks, one sees S-band holding steady for Earth-linked tasks and mid-speed science transfers [8–11]. At the same time, reviews of CubeSat antennas point to patches and slots tuned for S-band as well-tested solutions, particularly when mounted across different sides or paired smartly to ease reliance on precise orientation [12–15].

What makes digital twin research matter here isn't obvious at first. It lets engineers check how a part works even when the physical version hasn't been built yet. In satellites, these models help spot failures, track condition, study heat flow, mimic power networks, plus run tests that mirror real space missions [16–20]. One idea keeps appearing - good twins go beyond basic simulations. They link guesses, expected actions, and real results in a cycle you can test again and again. When it comes to small satellite radios, such an approach means pulling together orbit paths, signal strength limits, contact windows, battery levels, along with operating modes inside a single setup that runs reliably every time.

3. Mission Requirements and Assumptions

A small satellite, shaped like a box measuring 30 by 20 by 10 centimeters, fits the usual size for a 6U design. For sending data back and forth, it uses S-band signals, handling both system updates and scientific information. This setup exists within a test simulation, not an actual flight-ready plan.

Around each flight program, orbital plus ground-segment aspects take shape through set assumptions. These choices stay cautious, practical for engineering needs, yet broad enough to avoid suggesting proven hardware is ready now.

Mission setup begins here. At 500 kilometers up, the craft circles Earth on a smooth, round path tilted just right for sunlight tracking work. Down below, equipment waits near the middle latitudes: a dish two-fifths of a meter wide, shaped like a bowl to catch faint signals. This gear listens using S-band frequencies with quiet internal electronics so weak pulses are not lost. Signals flow through software-defined radio tools instead of hardwired boxes. For sending data back, engineers pick 2.25 gigahertz as the core frequency, while commands coming in ride similar waves yet slower by necessity. Usable contact starts when the craft lifts past ten degrees above the horizon line. Higher angles, say twenty and beyond, are better due to fading links, beam shape limits, and air effects stacking up unpredictably. End point reached.

Despite any misalignment of the spacecraft, command access stays active through every safe mode. When conditions allow better transmission, science data flow increases, yet never exceeds available power or heat tolerance. Fitting within a 6U form factor shapes how parts are chosen, along with keeping energy use practical. Antennas designed for variety in signal reception support reliability. Modulation shifts on its own, adjusting to current link quality. Coding follows suit, matching each change in environment. A twin-like control system tracks orbit position and battery levels, then updates operations accordingly.

One thing to note first: Table 1 holds the core ideas shaping everything after it. Each number shown later comes either from those starting points or common engineering formulas. A label clearly marks values picked by design, not measurement. What matters here is knowing where each figure originates.

Table 1. Assumed mission and subsystem parameters used in the analytical model.

Parameter	Assumed value	Notes / rationale
Orbit	500 km circular LEO	Representative small-satellite mission
Inclination	Sun-synchronous class	Used for pass variability only
CubeSat size	6U, 30 × 20 × 10 cm	Mission envelope provided in the prompt
Downlink band	S-band, 2.25 GHz center	Common CubeSat S-band practice
Uplink band	S-band family, lower command rate	Same band family for subsystem consistency
Nominal RF output	1 W	Energy-aware nominal operating point
Burst RF output	2 W	Used only when link margin and battery state permit
Onboard antenna gain	7.5 dBi per patch	Body-mounted circularly polarized patches
Ground antenna gain	26.8 dBi	1.2 m class dish at S-band
Receiver NF	1.5 dB	Lumped receive-chain assumption
Miscellaneous loss	4 dB	Feeder, pointing, polarization, atmosphere, implementation
Nominal bit rate	1 Mbps	Mid-pass science downlink
Burst bit rate	2 Mbps	High-elevation buffer dump
Contingency bit rate	256 kbps	Safe-mode or low-margin operation
Coding family	CCSDS-compatible adaptive coding	Exact code rates chosen by mode
Pass elevation floor	10°	Conservative acquisition assumption

4. Proposed S-Band Communication Subsystem Architecture

Look at Figure 1 - it outlines the suggested layout of the subsystem. Starting from the on-board computer, mission data gets packed into CCSDS format. From there, that data moves to the baseband processor. This unit handles channel coding; sometimes it shuffles bits using interleaving, then maps symbols. Once processed, the signal reaches the modem, forming an analog wave. Meanwhile, a frequency synthesizer works alongside the RF front end. Together, they shift the signal to S-band frequencies. Amplification follows. Afterward, the boosted signal travels via a switchable antenna setup. Two patch antennas, circularly polarized, sit on opposite sides of the spacecraft. They send out the transmission. Each piece links step by step, with no gaps.

The ground station performs the inverse operations using a high-sensitivity receive chain and a CCSDS-compatible decoder.

Choosing two patch antennas instead of a single foldout design was intentional. Right after launch, a 6U CubeSat cannot rely on perfect alignment with Earth due to limited frame stability across every orbit pass. Circularly polarized patches fixed to opposite sides cover parts of both halves of the satellite and work better across varying roll positions while allowing switchable signals if one side faces away. One face blocked? Another stays active. This antenna type will not deliver peak signal strength, yet balances straightforward build needs, minimal failure chances, and broad reach - key for power-smart data transfer.

Out in the open, updates shape how the RF chain works. Built on SDR or FPGA, the baseband skips full reworks when swapping modulations or codes - no touch needed on the analog side. Since testing happens through simulation early, developers run the exact signal path seen later on actual gear. Even though that part runs familiar tricks - clean boost incoming, mild push outgoing, filter cuts, split paths - the way everything locks together stands out. Innovation hides not in new parts but in how they join. What matters grows behind arrangement.

Down here, raw mission data gets packed using CCSDS rules before turning into signals. Instead of simpler methods, QPSK handles the transmit job - it keeps things efficient without overcomplicating design. Coding is not fixed; during lock-on and low sky passes, a tougher but slower code runs. As the satellite climbs higher, a faster code takes over - this happens when signal loss drops most. By shifting rates like this, each orbit finishes transmission quicker overall. Less time transmitting means less power burned for every piece of data brought home. The system wins on energy by timing high volume right, not by sticking rigidly to one speed through varying skies.

Instead of imagining a faraway space facility, the setup acts like a compact ground station. Picking this route matters since relying on massive antennas would not reflect how a real 6U satellite communicates. Think of the base station as having a dish about 1.2 meters wide, fitted with regular low-noise hardware and an SDR to decode signals. Tough? Yes. Impossible? Not at all - universities or local teams could pull it off, making it fit just right for a CubeSat digital counterpart.

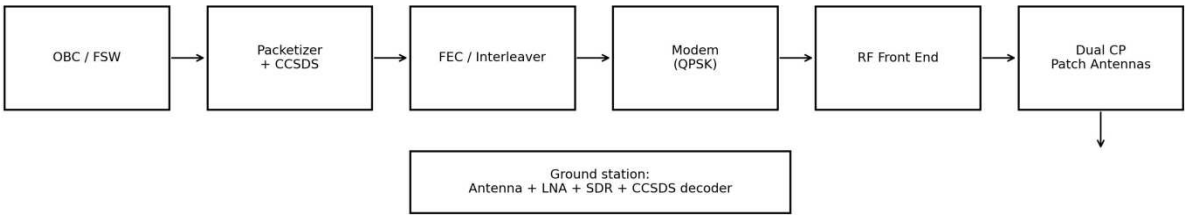


Figure 1. Overall communication subsystem block diagram for the proposed 6U CubeSat architecture.

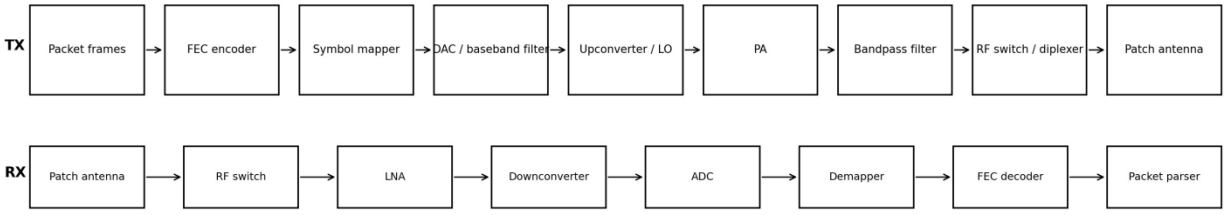


Figure 2. Transmit and receive RF/baseband chain used in the virtual-twin model.

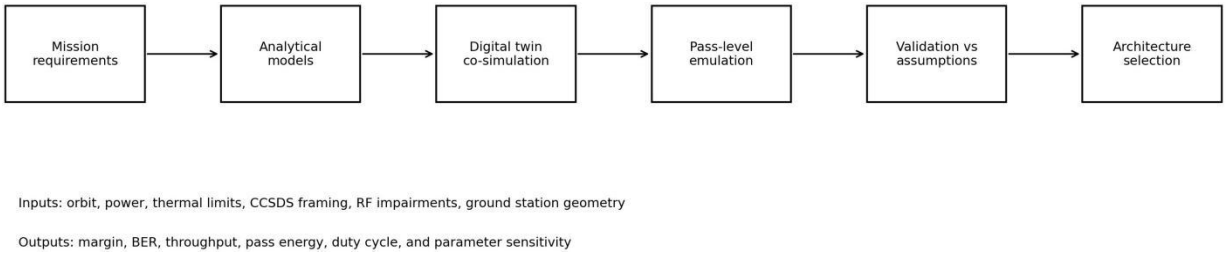


Figure 3. Virtual-twin workflow linking mission assumptions, analytical models, pass simulation, and architecture selection.

5. Analytical Modeling and Link Budget

The downlink link budget is computed using standard free-space path loss and receiver-noise relations. The received carrier power is

$$P_r = EIRP + G_r - L_f s - L_m isc,$$

where EIRP is the effective isotropic radiated power, G_r is the ground-station antenna gain, $L_f s$ is the free-space loss, and $L_m isc$aggregates feeder loss, polarization mismatch, atmospheric attenuation, and pointing uncertainty. For a circular orbit at altitude h and elevation angle e, the slant range is

$$rho(e) = -R_E \sin(e) + sqrt[(R_E + h)^2 - (R_E \cos(e))^2],$$

with R_E the Earth radius. The free-space path loss at frequency f is

$$L_f s(dB) = 92.45 + 20log10(f_G Hz) + 20log10(rho_k m).$$

Noise power is estimated from

$$N(dBm) = -174 + 10log10(B_H z) + NF,$$

where B is the receiver noise bandwidth and NF is the receiver noise figure. The carrier-to-noise ratio is therefore $C/N = P_r - N$.For digital links, a more useful metric is Eb/N0, obtained from

$$Eb/N0 = C/N + 10log10(B/R_b),$$

where R_b is the bit rate. These relations make the effect of modulation and coding explicit: a higher-rate mode requires either more link margin or more power, while a lower-rate mode can operate deeper into the pass but at the cost of longer transmit time. One watt stands as the standard RF output power in this modeled setup, while two watts come into play during burst operation. Starting with signal strength, each patch on board delivers an estimated 7.5 dBi antenna gain. Feeder lines and switching components chip away at that figure by roughly one decibel. A ground setup using a 1.2 meter S-band dish targets a receiving gain near 26.8 dBi. Factoring in real-world hiccups, four decibels account for various propagation setbacks plus hardware imperfections. This number walks a line - higher than ideal, yet shy of worst-case predictions. Every value here serves modeling purposes only, not actual performance data from hardware flights.

Power needs get figured out per subsystem, not each tiny part. When sending data normally, the computer and signal processor pull close to 1.3 watts, while the radio section uses near 2.6 watts. Keeping orientation stable takes around 0.8 watt. Heat control and extra tasks add roughly 0.3 watt, adding up to some 5 watts during active talk time. Firing in short

bursts pushes that draw to nearly 6.6 watts. Listening quietly or coasting between tasks cuts demand sharply. What matters most? Talking only when needed keeps energy use low. Power hits peak just when transmitting happens. Managing how often that occurs shapes the whole savings game.

Heat builds fast in the transmitter. Even with decent efficiency, a 1 watt signal throws off multiple watts as warmth, forcing operations into short bursts instead of nonstop runs. The digital model ties activity windows to where the satellite sits in orbit and how much juice remains in storage. That timing is not just background logic - it keeps the system alive, since overheating, just like running out of energy, could drag transmission speeds down when contact lasts too long.

Table 2. List of core equations used in the analytical model.

Equation	Expression
Eq. (1)	$P_r = EIRP + G_r - L_fs - L_misc$
Eq. (2)	$rho(e) = -R_E\sin(e) + sqrt((R_E + h)^2 - (R_E\cos(e))^2)$
Eq. (3)	$L_fs(dB) = 92.45 + 20log10(f_GHz) + 20log10(rho_km)$
Eq. (4)	$N(dBm) = -174 + 10log10(B_Hz) + NF$
Eq. (5)	$C/N = P_r - N$
Eq. (6)	$Eb/N0 = C/N + 10log10(B/R_b)$
Eq. (7)	$R_b = kR_s$
Eq. (8)	$E_b = P_avg/R_b$
Eq. (9)	$eta_E = bitsdelivered/joule$
Eq. (10)	$P_avg = sum_i(D_iP_i)$
Eq. (11)	$D_TX = t_TX/T_pass$
Eq. (12)	$Margin = (Eb/N0)_available - (Eb/N0)_required$

Table 3. Downlink link-budget summary for the selected nominal 1 W mode.

Elevation	Range	FSPL	C (dBm)	Eb/N0 (1 Mbps)	Eb/N0 (2 Mbps)
10°	1695.1 km	164.1 dB	-105.3	7.2 dB	4.2 dB
20°	1193.0 km	161.0 dB	-102.2	10.3 dB	7.3 dB
30°	909.5 km	158.7 dB	-99.9	12.6 dB	9.6 dB
45°	683.1 km	156.2 dB	-97.4	15.1 dB	12.1 dB
60°	570.5 km	154.6 dB	-95.8	16.7 dB	13.7 dB
90°	500.0 km	153.5 dB	-94.7	17.8 dB	14.8 dB

Table 4. Communication-mode power budget used in the virtual-twin model.

Mode	OBC/FPGA	RF chain	ADCS/pointing	Thermal/other	Total
Safe beacon	1.0 W	0.4 W	0.2 W	0.2 W	1.8 W
TT&C receive	1.2 W	0.7 W	0.4 W	0.3 W	2.6 W
Nominal downlink	1.3 W	2.6 W	0.8 W	0.3 W	5.0 W
Burst downlink	1.4 W	3.8 W	1.0 W	0.4 W	6.6 W
Idle cruise	0.8 W	0.0 W	0.1 W	0.1 W	1.0 W

The link-budget results above are the basis for the pass-level simulation. They show that the nominal 1 W architecture is not a one-rate radio; instead, it is a rate-scheduled radio whose efficiency depends on orbital geometry.

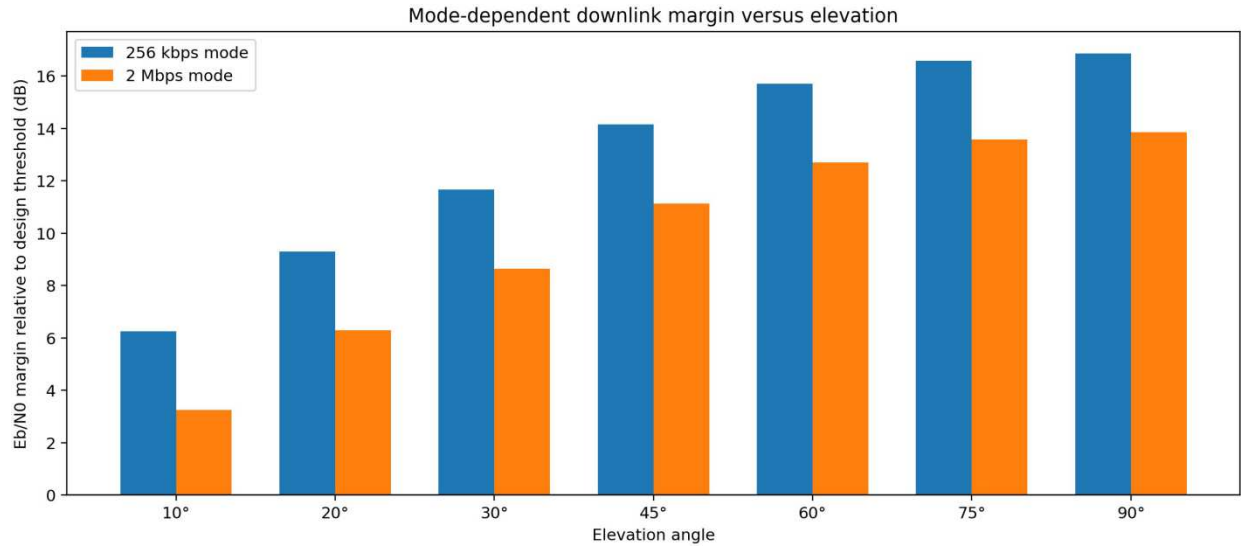


Figure 4. Eb/N0 margin relative to the design thresholds for selected downlink modes versus elevation angle.

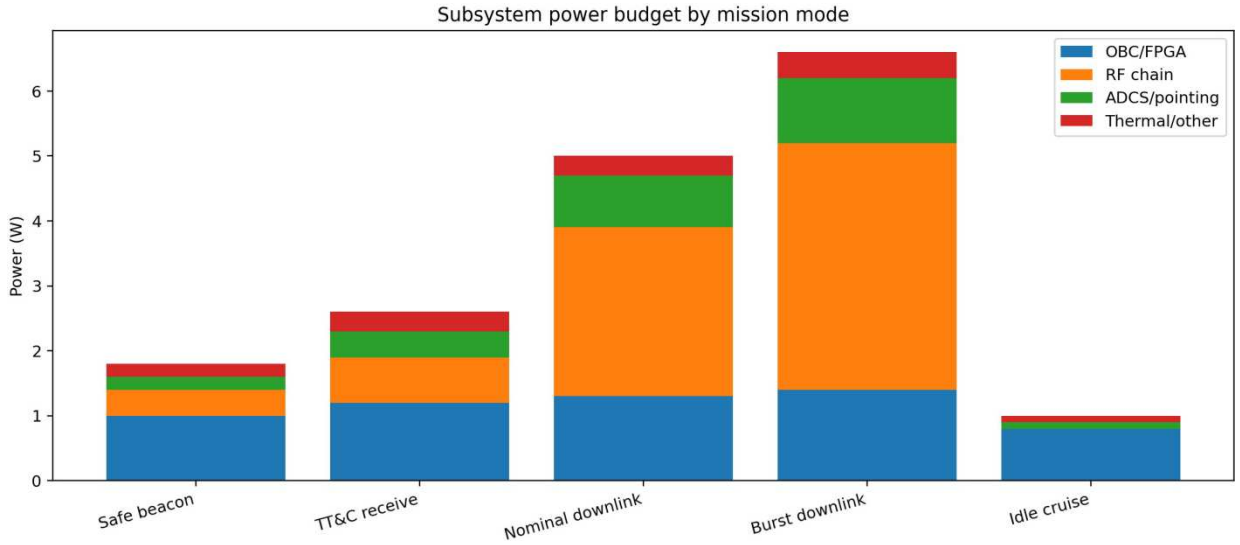


Figure 5. Communication-mode power budget partitioned into OBC/FPGA, RF chain, attitude support, and thermal/auxiliary loads.

6. Virtual Twin Simulation Methodology

A virtual twin connects an analysis setup to a pass-level run. Not built like a detailed mesh of parts, it acts more like a working replica shaped by radio rules, path curves, energy shifts, and how tasks switch during flight. This line exists because picking comms gear is not about testing one chip inside an amp - it is about seeing if everything moves enough data without overheating or draining too fast when flying real orbits.

From mission needs and clear assumptions, things begin. Elevation shapes how the analytical model figures out link margin, energy per bit, and pass time. As the simulation moves across an orbital window, it shifts radio behavior step by step - starting slow and strong at first contact, moving into regular operation halfway, then speeding up only if signal conditions allow. Alongside, the virtual twin logs incoming power levels, data speed, total energy used, and expected delivery of packets. What comes out in the end is a validation report showing whether the architecture remains inside the feasible envelope under the assumed conditions.

Checking things line up matters more than matching gear here. Before anything flies, the model gets tested on whether numbers make sense - like whether energy spent equals energy planned. Power totals need to balance. Time used cannot stretch beyond the window available. The chosen signal method has to stay under the needed signal quality limit. Heat produced must fit what cooling can handle. When one rule breaks, the system says no - even if radio performance looks fine on paper.

A twist in the setup shifts antenna strength, signal output, and receiver sensitivity inside the twin model. Small satellites often run so close to limits that even a slight drop - just 1 dB - can push good connections toward failure. Because of this tight margin, adjusting these factors shows how tough the system really is. Rather than trust one clean budget chart, this method reveals what happens when things are not perfect.

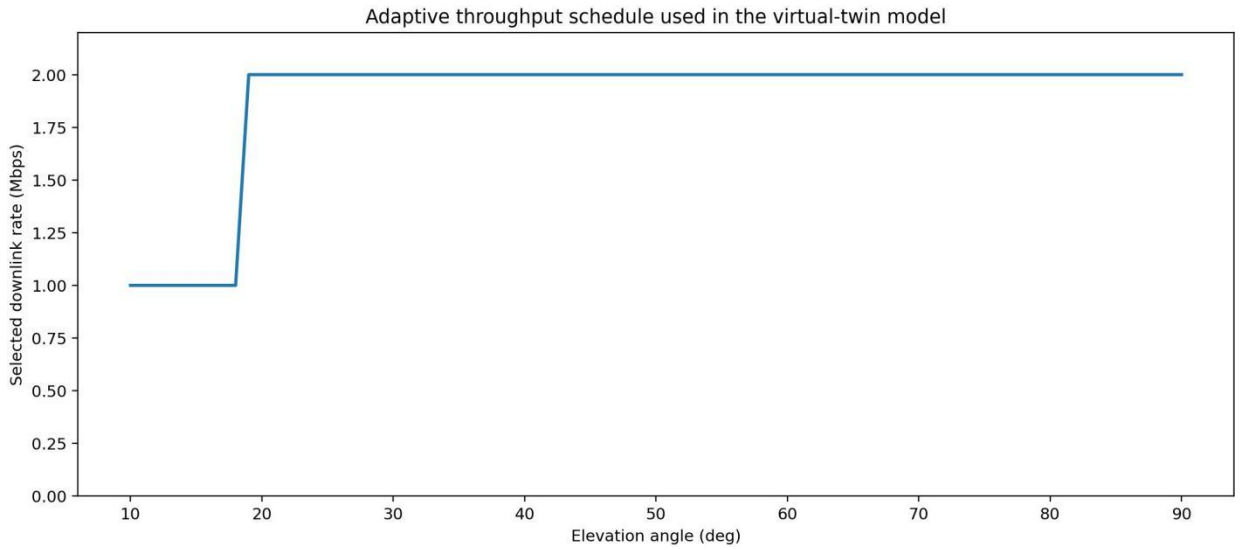


Figure 6. Adaptive throughput schedule selected by the virtual-twin controller as a function of elevation angle.

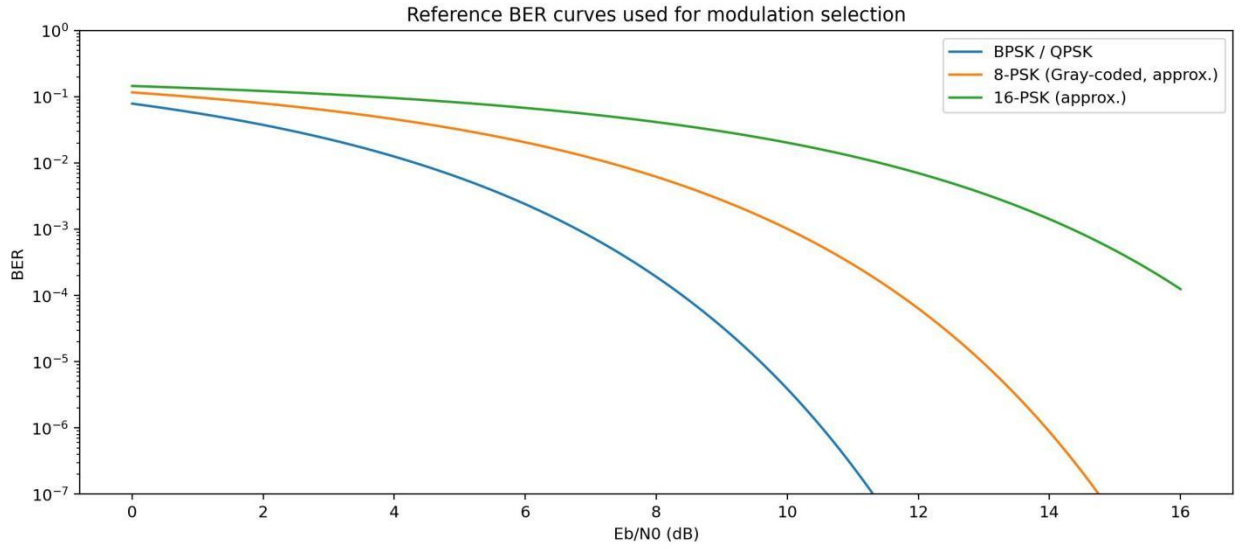


Figure 7. Reference BER curves used to justify modulation selection in the selected architecture.

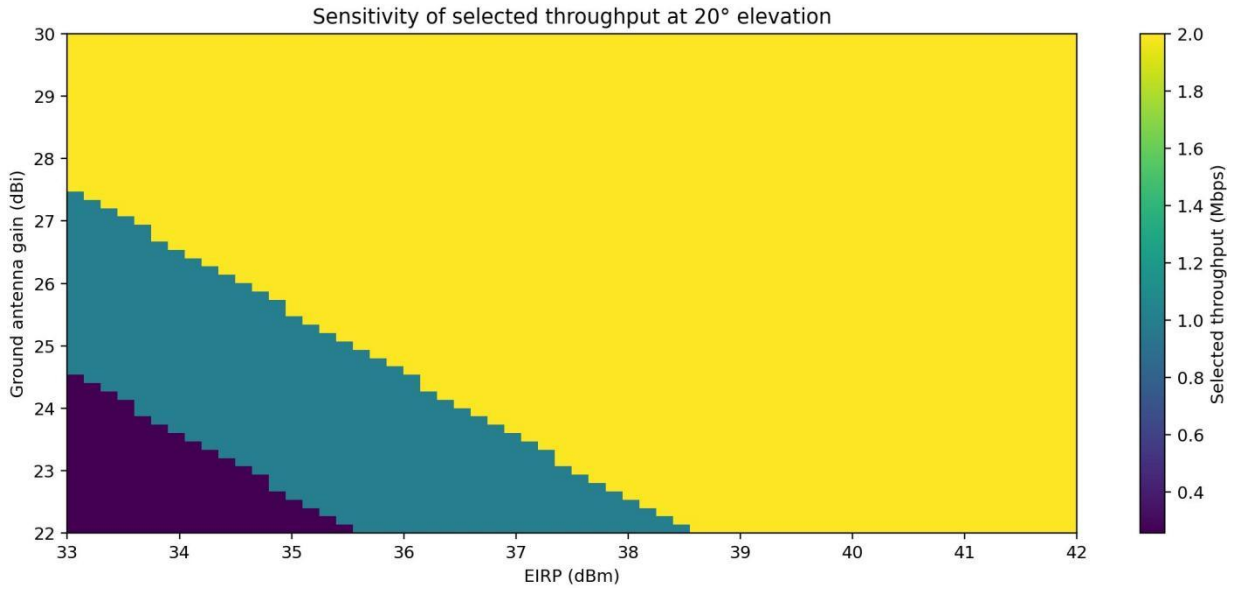


Figure 8. Sensitivity of selected throughput to EIRP and ground-antenna gain at 20° elevation.

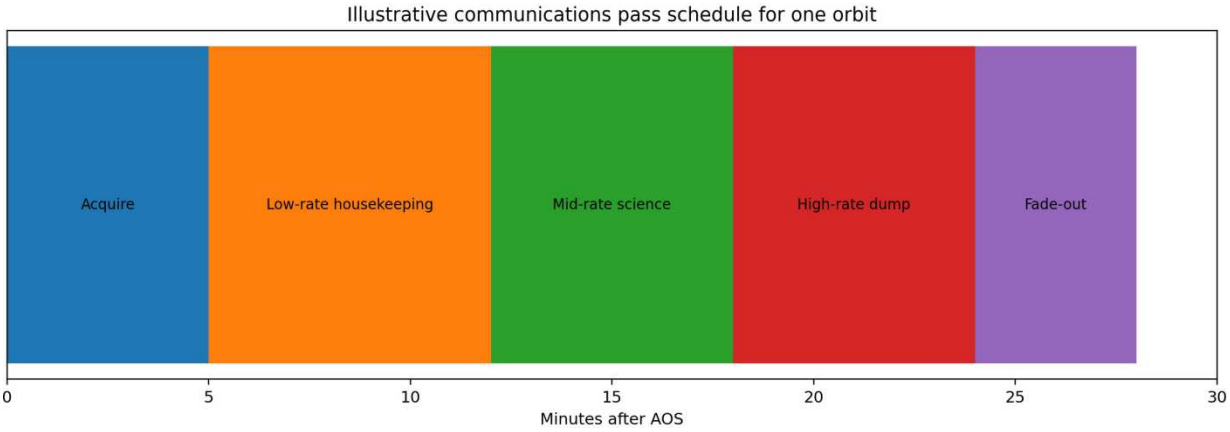


Figure 9. Illustrative communication-pass schedule showing the transition from acquisition to burst downlink.

7. Results and Discussion

Even with the given assumptions, the chosen setup keeps a positive signal margin at every modeled angle. Though near 10°, only the 256 kbps backup option holds up well, the 1 Mbps setting stays usable through much of the satellite's path. Above about 20° to 30°, bursts at 2 Mbps start making sense - exact angles depend on how efficiently things are built. What matters most is not universal coverage per mode, but rather how smart switching fits each part of flight with its best match.

Because of height changes, the system adjusts data flow on its own. When flying low, signals travel farthest, so stability matters most. In middle altitudes, the connection shifts toward regular science speeds instead. Near the top, short bursts activate just long enough to clear stored data. As a result, the twin’s signal looks like steps going up - not a straight bar - and that matches what it should be.

Out there, a small satellite talks best not by sticking to one speed. Instead, it uses where it is in its path. The shape of the journey shapes how fast it shares data. Not locked into slow or fast. It shifts as it moves through space. What matters is location, moment by moment. Efficiency comes from motion, not fixed rules.

Even though QPSK shares the same basic bit error rate formula as BPSK in noisy channels, its tighter signal spacing helps save space on the radio dial. Instead of stretching across frequencies, it packs data neatly - useful when satellite room is tight. Moving up to fancier phase tricks might move more bits, yet those need stronger signals just to hit average performance marks. Since small satellites face shaky alignment, line losses, and shifting heat, wasting headroom there makes little sense. Not only does the math allow QPSK, it quietly insists.

A closer look at the power setup shows something hidden. Not every fast method burns more energy per bit sent. With this particular setup, sending data in quick bursts takes high power for a short time, yet ends faster - which means less total energy used per bit compared to slow, drawn-out transfers. That surprise insight drives smart energy choices: if the connection can handle it, pushing data hard and finishing early beats crawling along with a thin, wasteful signal. Finishing quickly wins.

Heat levels match what the power data predicts. Holding the transmitter on nonstop would push multiple watts into the thermal system over extended periods - too much for a 6U satellite with little surface to shed heat. Instead of running constantly, signals go out only when contact windows allow, while downtime lets components cool down. This approach holds heat stress within limits. The setup works not from brute strength but through careful timing and restraint.

8. Comparison with Alternative Architectures

Looking at three possible designs, one stood out. A basic setup came first - using steady speeds, simple signals, and low complexity. Easy to build, uses less energy. Yet it misses chances when flying high, stuck with old settings. Then another option stepped in - a smart radio shifting rates, built for change. Antennas worked together, and hardware adapted on the fly. Tougher? Yes. Still fits inside a small satellite frame. Performs well where others lag, handles shifts without fail. The last choice brought no real gain over this middle path. Apart from the others, one choice pushed speed through advanced signal shaping and tighter code settings. This version moves the most data at its core, yet brings tougher setup demands alongside sharper alignment needs. Risk climbs when putting it in place, simply because everything must fit just right.

Not just top speed settles this choice. A CubeSat works better when breakdowns happen rarely, it handles more orientations, and it moves data efficiently once every drawback shows up. Out comes the folding antenna - shaky on reliability. The set-speed approach? Lags behind when getting work done. Only the shifting double-pad model keeps standing through both emergency checks and research tasks. Simulating it feels smoother too, since basic radio math and power rules cover its behavior - no complex moving parts to guess at.

Looking at different types of antennas gives a similar result. One basic omnidirectional antenna is handy - yet too weak for long-term science data transfer. High-gain models boost speed, though they bring extra risk; using them on a 6U satellite makes little sense without solid attitude control and proven deployment methods. On the flip side, pairing two fixed circularly polarized patch antennas works well - they are straightforward, skip any moving parts, and pair easily with a simple software-defined radio setup on the ground.

Table 5. Comparison of candidate communication architectures for the 6U CubeSat.

Option	Antenna concept	Modulation / coding	Complexity	Risk	Assessment
A	Single low-gain fixed antenna	BPSK or QPSK, fixed low-rate coding	Low	Low hardware risk; poor mission efficiency	Robust but capacity-limited
B	Dual CP patch diversity	Adaptive QPSK, CCSDS-compatible coding	Moderate	Balanced implementation and mission performance	Selected architecture
C	Deployable high-gain antenna	Higher-order PSK/QAM with stronger coding	High	Deployment and pointing sensitivity	High throughput, higher risk

Table 6. Candidate antenna and modulation combinations considered in the design trade.

Combination	Typical gain	Key advantage	Key limitation	Use case
Body-mounted monopole/dipole	Low	Simple and tolerant of attitude error	Low S-band gain	Beacons and very low-rate backup
Body-mounted CP patch pair	Moderate	No deployment event; good diversity	Lower peak gain than deployable options	Nominal CubeSat S-band downlink
Deployable patch array / mesh	High	Best raw link margin	Higher integration and qualification cost	Aggressive high-rate missions

9. Limitations and Future Work

Most of the results face a single hurdle. These insights emerge from simulated environments — digital setups replacing actual flight tests. Because of that, the safety figures trace directly back to those virtual runs, leaning only on early assumptions made at the start. Individual components do not each carry full physical modeling — the way signals travel and how warmth builds get bundled into broad categories by design. Later on, actual hardware plans must study signal fading, timing mismatches in waves, antenna behavior during detuning, hot zones in circuits, together with effects caused by cosmic radiation. One thing stands out — this Earth-based system works like a single dish roughly 1.2 meters across, whereas true operations could combine multiple stations varying in power and ambient noise.

One step forward might be testing with live gear — hooking up a real software-defined radio along with the right radio frequency setup works more like the real thing. When satellites spin or tilt, their antennas do not point precisely, and that shift changes how signals spread out, often weakening them rapidly when viewed from sharp angles. Another angle? Let systems break slowly in simulation — batteries fading, amplifiers drifting off track, maybe one antenna arm barely functioning. Toss those pieces in, and what once felt like an idea starts acting like the physical version would in orbit. Later phases lean into hardware-in-the-loop checks since real parts under stress react differently than clean models predict.

10. Conclusion

What makes this design work well is not flashy components. Instead of loading up on powerful gear that eats through power and space, it avoids going too far in the other direction — skimping on communications when data matters. Most small satellites live or die by how they handle trade-offs like these. This version uses an S-band setup tuned for efficiency, adjusts modulation as needed, follows standard data framing, runs two patch antennas, relies on reprogrammable hardware for signal handling, and fits neatly between extremes few missions can afford. Success hides in choices like this one.

A different way of testing shows real value. When link budgets connect with timing rules, signal paths, and energy limits inside one running model, choices gain clarity early on. This setup cuts the chances of errors later, reveals quiet compromises, and shifts discussions toward facts instead of guesses. Out in actual use, it separates gear that runs only under perfect conditions from systems built to last in space.

Truth be told, the chosen setup fits a 6U CubeSat well since it plays safe when the mission needs trustworthiness, yet takes chances if speed can slip through. Another reason it makes sense? The design does not dream too big — it stays grounded where it counts.

Most big decisions here hold up when measured. Friendly for deployment, the antenna makes field work easier. Spectrum use stays lean without pushing limits through modulation choices. Coding aligns smoothly with current CCSDS methods. Ground operations run on minimal yet reliable setups. On small satellites, these pieces together turn ideas into working systems.

Appendix A. List of Figures and Graphs Required

Figure	Caption / purpose
Figure 1	Overall communication subsystem block diagram
Figure 2	S-band RF chain diagram
Figure 3	Virtual twin workflow diagram
Figure 4	Link budget bar chart / margin-versus-elevation plot
Figure 5	Power budget pie chart or stacked bar chart
Figure 6	Throughput vs elevation angle graph
Figure 7	BER vs Eb/N0 graph
Figure 8	Duty-cycle vs orbital phase graph
Figure 9	Trade-off matrix comparing protocol options
Figure 10	Sensitivity analysis heatmap
Figure 11	Mission timeline / communication pass schedule infographic
Figure 12	Comparison table of candidate antennas and modulation schemes

Appendix B. Figure Captions

Figure 1. Block diagram of the complete communication sub-system designed for the proposed 6U CubeSat platform.

Figure 2. RF and baseband transmit/receive chain design implemented within the virtual-twin communication system.

Figure 3. Work flow diagram of the virtual twin approach highlighting the connection between mission requirements, analysis and modelling, pass simulation, and selection of communication architectures.

Figure 4. Eb/N0 margin variation as a function of the elevation angle for downlink communication modes as compared with design thresholds.

Figure 5. Power consumption among communication modes, including OBC and FPGA, RF chain, attitude control subsystem, and thermal and auxiliary subsystems.

Figure 6. Throughput adaptive scheduling as output by the virtual-twin controller with respect to the elevation angle.

Figure 7. BER performance reference curves used for determining modulation types for the proposed communication architecture.

Figure 8. Throughput sensitivities as a function of the EIRP and G/GT values at 20° elevation angle.

Figure 9. Communication pass timing diagram showing the process from signal acquisition to the burst downlink mode..

Appendix C. Conclusion

Most of what makes this design work comes down to staying balanced. Too much power poured into comms eats up everything a 6U satellite has to offer, yet skimping on the radio risks losing data worth collecting. Sitting between those edges is an S-band setup tuned for efficiency, shaped by smart QPSK shifts, framing that plays well with CCSDS rules, two patch antennas facing different ways, plus signal handling through reprogrammable chips. That midpoint - neither flashy nor barebones - is where small satellites often succeed or fail.

A different way of testing matters just as much. Instead of building first, math models for signal strength team up with timing rules, path shapes, plus on-off cycles inside one running test. This shows how things will perform long before parts are bought. Risks drop when problems surface early. Choices become clear through data instead of guesses. The outcome? A radio might function fine indoors yet fail above Earth - this process helps avoid that gap.

Putting it together, the setup makes sense for a 6U CubeSat - it plays safe when dependability matters most, yet takes advantage of openings for better performance where possible. What helps? Each key decision holds up under numbers: the antenna works smoothly with standard deployment systems, the signal method uses bandwidth well without pushing limits, error control follows current CCSDS standards, while Earth-based operations rely on equipment that's basic but fully functional. With tiny spacecraft, such balance changes an idea into something real.

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