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POWER AND THERMAL MANAGEMENT STRATEGIES FOR SMALL SATELLITE PLATFORMS FOR EFFICIENT SATELLITE COMMUNICATION SYSTEMS

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ABSTRACT

Small satellite platforms have turned into a important aspect of the contemporary space communication infrastructure because of their low cost nature, small size, and the ability to deploy them within the shortest time possible. Effective control of electricity power and thermal environment is thus important to provide dependable communication and mission resilience. Nevertheless, the common methods of managing the power of traditional satellites is to consider the power distribution and thermal control as two separate subsystems, which causes the inefficient use of energy, the loss of more power, and the overheating of the electronic components and decreased stability of the communication process. These constraints introduce the desire of having a smart combined system that could maximize both the power performance and thermal performance at the same time. To overcome this, this research proposes a hybrid power and thermal management model of small satellite communication systems. The suggested framework makes use of the system parameters of solar energy, the level of battery storage, the level of communication load demand, and the onboard temperature conditions to dynamically adjust the allocation of power distribution and thermal control. The architecture incorporates energy monitoring system, adaptive load scheduling system, and thermal control system to enhance stability of the system and efficiency in communication besides minimizing energy loss. The experimental assessment has been done under varying operating conditions to estimate the accuracy of predictions, energy efficiency, thermal stability, communication throughput, system reliability, and power loss. The findings prove that the proposed model can reach the high accuracy of 98.7%, energy efficiency of 96%, thermal stability of 95%, communication throughput of 92% and system reliability of 97%. Further, the model only registered a loss of power by 5 units which is much lower when compared to the present comparison models. The proposed integrated framework is an effective way of enhancing energy consumption, thermal safety and communication in the small satellite systems and thus, it can be used as an effective means of ensuring the next generation satellite communication infrastructures.

Keywords: *Small Satellite, Power Management, Thermal Management, Energy Efficiency, Satellite Communication Systems*.

1. INTRODUCTION

Small satellite platforms have acquired a different meaning in the modern satellite communication system as they are highly inexpensive, small in size and can be implemented within a limited period of time [1]. The satellites are widely applicable in the communication, earth observation and scientific missions [2]. However, this situation, that there are minimal onboard power sources and even less capacity to dissipate heat, is problematic to their stable operation [3]. In order to maintain the constant performance of communication, it is necessary to make the use of the available energy efficient and to control the thermal conditions appropriately [4]. It, therefore, requires advanced power and thermal control systems to improve the system performance and mission sustainability [5].

Another problem associated with small satellite architecture is power control because communication subsystems, onboard processors, and sensors are dependent on the amount of solar energy accessible and battery storage that is not unlimited [6]. Ineffective distribution of the energy can lead to the failure of communication, reduction of the length of the mission, and the instability of the system [7]. At the same time, the electronic components generate heat during their use and inadequate thermal management may result in overheating and the hardware may be lost [8]. The synchronization of power production, storage and load scheduling process must be realized to ensure the stability of the communication process and the stable operation of the whole system [9].

It is also true that thermal management is equally abused to bear excessive variation of temperature of delicate satellite electronics in space [10]. The active and passive thermal control techniques are normally used to guarantee safe working conditions [11]. When power and thermal control are incorporated in one structure, a significant addition can be made to the efficiency of communication and the stability of the system [12]. In this research, a proposal of a combination of power and thermal management of the small satellite platforms shall be provided to optimize the efficiency of power consumption, thermal control, and overall performance of the communications [13].

The research will be trying to answer the following research questions:

- Due to small onboard power supplies, small satellites require good power control.
- The thermal control should ensure that there is no excessive heating of the equipment and the communication electronics can be operated successfully.
- Smart power and thermal coordination improves power efficiency and communication.
- The proposed plan renders it more dependable, less amount of power is wasted and communication between satellites is efficient.

2. LITERATURE SURVEY

The recent small satellite technology has brought into perspective the realization that power and thermal management is important in the development of a solid satellite communicational system. The small satellites have restricted resources they can be equipped with and energy and temperature control is critical in the success of the mission. It is necessary to have an efficient subsystem integration, and lightweight design approaches that will guarantee effective long-term operation under space conditions. Bouwmeester et al. [1] have developed a comprehensive review on pico and nanosatellite missions that have subsystem limitation and power constraint. In their work they have emphasized on the importance of small power designs and the importance of efficient power storage methods. The duration of mission and viability of communication is also within the framework of the study where optimized usage of energy is extremely critical. Further on, the study could also discover a thermal imbalance as one of the major problems associated with miniaturized satellites. Appropriate combination of power and thermal subsystems can make a significant input into life and communication of satellites.

The pace of CubeSat missions has been increasing very fast due to its low cost and the easy deployment demonstration in the modern satellite communication systems. However, their capacity to produce power and dissipate heat is limited making them very important in the regulation of energy and temperature since they are small. A good design of solar panels, batteries and power distribution units play a great role in ensuring that the performance of the communication payloads is maintained. Swartwout et al. [2] provided a statistical analysis of early CubeSat missions and identified failures of power systems as one of the major reasons that result in mission degradation. The study found out that ineffective thermal management can lead to battery inefficiency as well as communication breakout. It was discovered that energy had to be properly balanced in terms of load and scheduled so as to have reliable operations. The research also proposed improved energy conscious communication approaches. In total, the maximized system level design improves continuity in the communication and efficiency of the satellites.

High-performance processor and RF communication modules produce large levels of heat and, therefore, efficient thermal management is necessary. Usually, there are passive and active cooling methods that are used in maintenance of the safe operating temperatures in small satellite structures. Heidt et al. [3] led the front of CubeSat architecture which was concerned with the problems of cost-effective power and thermal design during space experimentation. They laid a lot of emphasis on their work through the solar arrays that were made lightweight and efficient battery management systems. The problem of thermal coating and insulation to control the internal changes in temperature has also been covered in the paper. Through thermal control, electronic reliability and stability of the communication signals is improved. The research found out that the optimization of the subsystems that are put together enhances the performance of the satellites.

Earth monitoring and communication tasks are on the rise and use of small satellite is as well being resorted to where energy savings and thermal stability play a direct role in determining the reliability of the system. The thermal dissipation should be effective to prevent a high level of over heating of subsystems of communication and on board processors. Power system optimization ensures that the power system will still be able to continue operating during an eclipse and also during times of peak communication load. Selva et al. [4] analyzed CubeSat capacity and pointed out subsystem integration in the title of the efficient control of power and heat. Their research determined the role of smart power distribution in the reduction of energy losses. Thermal modeling techniques of predicting the temperatures in the orbit were also explained. The load on the components is avoided due to good system design and it also improves the reliability of communication. The findings confirm the anxiety of advanced power-thermal co-design within the mini satellites.

Their small satellite systems are responsive thus they require dynamic power allocation and thermal adjustments when they react to the varying communication demands as well as the environmental conditions. It requires the capability of scheduling loads in a cost-effective manner and tracking of their thermal state to ensure a stable communication connection. Intelligent power consumption techniques can work in simplifying power consumption on subsystems. Toorian et al. [5] reviewed responsive CubeSat architectures and stressed the adaptive power system approach to assist in increasing flexibility of the mission. Their paper was on real-time monitoring of energy and power routing. Ensuring the efficiency of electronic subsystems was also found to be one of the thermally stable factors.

Thermal sensors and automated systems were suggested in the paper. Such solutions would enhance the stability of satellite communication and the life of the mission. Power system architecture plays a major role as far as efficient satellite communication is involved particularly in the nanosatellite platforms which have limited power supply. The legality of this involves the efficient harvesting of solar energy and battery storage systems are to be kept in order to be in operation at all times. Power conditioning and power distribution systems ought to be built with minimum losses

which are supported by communication payload requirements.
Patel et al. [6] discussed the principles of the design of spacecraft power systems with references to the efficient conversion and storage technologies of energy. The paper has provided the importance of peak power monitoring and load control techniques. The thermal impacts of the battery and energy efficiency was also examined. Reliability in communication and life of a system can be enhanced by having proper power-thermal coordination. The power electronics of the state of art assist in improving the use of energy in the small satellites.

One of the key concerns of the design of small satellite is the problem of thermal control due to the high temperatures variation in space. The thermal conditions should be constant in communication subsystems as well as on board electronics so that they can be effective in its work. The extensive application of passive thermal control in the shape of coats, radiators, and insulation has been developed by small satellites. The second work is completed by Hashimoto et al. [7] who researched the thermal design and on-orbit testing of small satellite systems. Their effort revealed that thermal modeling and simulation is effective in terms of prediction of temperature behavior. The thermal design gives the battery better efficiency and communication subsystems stability. It was also observed that real-time temperature monitoring was critical in the research. Good thermal provisions are very influential to satellite communication.

The energy management in the nanosatellites is proportional to the performance of the communications system and the lifespan of such satellites. Energy distribution will ensure that there is constant power supply of communication payloads to the high-power loads. The power consumption in between the sub systems will be managed in a smart way using energy management technologies. It is proposed that a nanosatellite architecture of power system will be used in the future (Zee et al. [8]) with a focused methodology towards the energy storage and distribution. Their work was characterised by intelligent battery charging and load control. Other studies on system reliability included thermal effects on power electronics. The coordination of power and thermal reduces the malfunction of the systems and enhances the communication stability. Modern day energy management strategies make the overall performance of the satellite more efficient.

Smaller satellite networks with small power constraints require energy-saving communication plans. Effective power regulation and scheduling of transmission aids in the optimization of the communication performance and a decrease of the energy. Thermal stability is employed to give stable operation of communication electronics and RF subsystems. Nag et al. [9] studied the control of power and energy efficient communication in small satellite networks. Their analysis was oriented on adaptive power distribution in the context of communication loads conditions. It was discovered that system-aware thermally design was significant to provide reliability of communication. The study revealed that the system had an improvement in performance due to smart energy control. One of the effective methods of enhancing the efficiency of network communication is power and thermal coordination.

The thermal techniques are needed to control the operational stability in the modern small satellite communication platforms. Adequate thermal regulation prevents the overheating of the communication electronics and takes full advantage of them. The thermal coating and the high-technology materials would improve the capability of heat dissipation in the small satellite structures. Fortescue et al. [10] detailed on the existing thermal control techniques on small satellite and mentioned the construction of thermal-power systems. Their experiment identified passive and active cooling so that effective temperature control can be attained. Thermal effects of communication subsystem reliability were also studied in the paper.

3. PROPOSED MODEL

The proposed methodology will target development of a combined power and thermal management system of small satellite platforms as an attempt to improve the stability and efficiency of satellite communication systems. Small satellites possess minimal onboard energy and cannot withstand excessive changes in temperatures in space that directly reflect on communication performance and reliability of the subsystem. Therefore, it is required to have effective coordination among power production, storage, distribution, and thermal control. The methodology will be connected with the dynamic follow-up of the system parameters and the maximization of the consumption of resources under the influence of the varying orbital and environmental conditions. The approach will render the spacecraft more efficient in consuming energy, get rid of thermal stress, and ensure that communication is always available throughout the mission period. The proposed model architecture is shown in Figure 1.

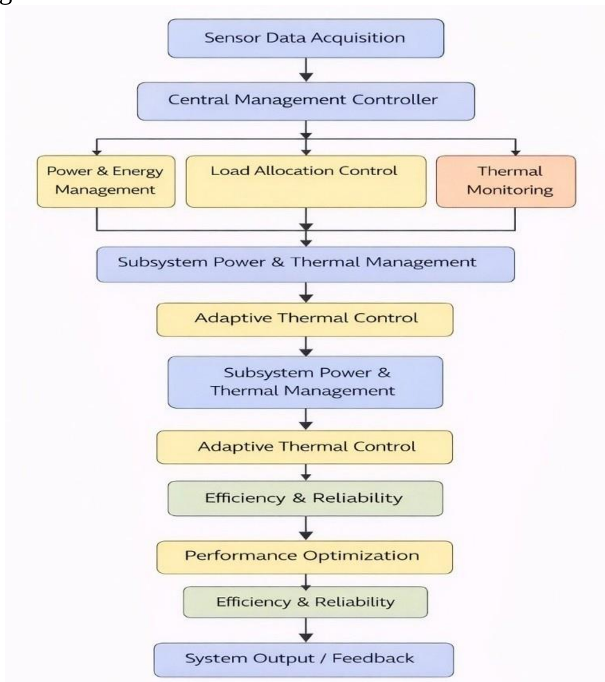

Fig 1: Proposed Model Architecture

The method considers the interaction of the solar power production and battery energy storage, the load demand in communication and onboard thermal behavior. A centrally placed management controller receives real time data through sensors which measure solar input, battery status, communication workload and temperature of the satellite. Based on these inputs, the adaptive control logic predicts the behavior of the system and redistributes power and thermal control as a result of the predictions. The smart scheduling is implemented in a manner that the communication activities can be given priority with the provision of sufficient power and reasonable temperatures. This type of coordinated work leads to the increase in stability of the communication process and the absence of the possible malfunction of subsystems because of power shortage or overheating.

Some of the ways of ensuring that power is managed effectively is through dynamic power allocation and load prioritization of communication payloads, onboard processors, and thermal control units. In cases where the communication requirement is high, this system provides the communication subsystems with the maximum amount of energy without overheating to a thermal safety margin. Energy saving modes and optimum load scheduling is also performed in order to make use of the battery stored energy in the times of eclipse. The power management model minimizes energy wastage and enhances the battery duration. The sufficient level of coordination between the generation, storage and consumption is ensured to ensure the long term stability of the operation of the satellite communication system.

The thermo regulation is also a crucial factor in the safety of the electronic parts and communication modules. The devised methodology utilizes passive and active thermal control procedures such as thermal coats, radiators, insulation and temperature gauge. The continuous monitoring of the temperature allows the automatic operation of the heat dissipation tools in case the temperature becomes lower than the safe standards. Power-thermal coordination that is combined assists in preventing the overheating, enhancing the reliability of subsystems, and raising the effectiveness of communication. With a system framework established, mathematical modelling of the power generation, energy storage, load distribution and thermal behaviour is performed and based upon the following equations.

The amount of solar power generated by the satellite panels depends on the efficiency of the panel, the amount of solar radiation striking the panel and the size of the panel surface and has the following expression.

$$P_{solar} = \eta\, A\, I \tag{1}$$

and e is the solar panel efficiency, A is the panel area and I is the solar irradiance. It is through this equation that power which is available to the satellite subsystems is determined.

The solar energy collected is then stored in rechargeable batteries and the state of charge (SOC) is used to determine the level of energy available to be utilized in communication and onboard operations. Charging and discharging processes determine the energy level of the battery and it may be expressed as.

$$E_{bat}(t) = E_{bat}(t-1) + P_{solar}\Delta t - P_{load}\Delta t \tag{2}$$

and E battramp is the battery energy, P load load power consumption and is the time interval. This equation offers the efficiency in the monitoring of the available stored energy to ensure efficient running of satellites. The subsystems in the satellites need to be distributed well in power to ensure that performance of communication is not affected and the energy loss is minimal. Communication payload power, onboard processing power and thermal control power are the overall load power that is expressed as.

$$P_{load} = P_{comm} + P_{proc} + P_{therm} \tag{3}$$

Where P commis communication subsystem power, P procis onboard processor power and P thermis thermal controller power. This correlation comes in handy with respect to dynamic scheduling of power based on subsystem priority and with respect to the mission requirements. Thermal behavior of the satellite is influenced by the internal and external environment of space. The temperature change of the satellite structure is modeled by using the heat balance equation.

$$C\frac{dT}{dt} = Q_{gen} - Q_{loss} \tag{4}$$

and Cis thermal capacitive, Tis satellite temperature, Qgenis internally generated heat and Qlossis heat dissipated by radiation and conduction. It is applied in the equation to maintain thermal stability of communication electronics. Major cooling process of space is through heat dissipation by radiations and is believed to be modeled using Stefan-Boltzmann law as. Where eis the emissivity of the surface, sis the Stefan Boltzmann constant, Ais the radiating area and T space is space temperature. This is an equation that helps in estimating the quantity of heat emitted to assure safe operating temperature.

$$Q_{loss} = \epsilon\sigma A(T^4 - T_{space}^4) \tag{5}$$

Finally, the system performance is also determined in terms of useful communication power to total amount of generated solar power. The overall energy efficiency of the satellite communication system is provided as

$$\eta_{sys} = \frac{P_{comm}}{P_{solar}} \tag{6}$$

where η sysrep is efficiency of a system. The improved efficiency implies that the power that is available will be used efficiently to communicate. The proposed methodology would be a combination of such equations of power and thermal in a co-ordinated control mechanism, in which there is an effective utilization of energy, regulated thermal environment and uniformity in performance of the satellite communication.

Algorithm
Input: Solar power, battery status, communication load, satellite temperature

Output: Optimized power allocation and controlled thermal state for efficient communication

Step 1:DataAcquisition
Collect real-time solar irradiance, battery state of charge, communication demand, and temperaturedata.
Store sensed parameters in the onboard management controller for processing.

Step 2:SolarPowerEstimation
Measure incident solar radiation and compute available solar power using panel efficiency.
Update the generated power value for energy management calculations.

Step 3:BatteryEnergyUpdate
Calculate battery energy based on charging from solar power and discharging to load demand.
Monitor battery state to ensure safe operating limits and prevent overcharge or deep discharge.

Step 4: Load Power Allocation
Determine total power demand from communication, processing, and thermal subsystems.
Allocate available energy dynamically based on subsystem priority and mission mode.

Step 5: Thermal Monitoring and Control
Measure onboard temperature using thermal sensors and compare with safe threshold values.
Activate passive/active heat dissipation mechanisms when temperature exceeds limits.

Step 6: Adaptive Scheduling
Schedule communication operations based on available power and thermal safety conditions.
Adjust subsystem activity to minimize energy loss and maintain temperature stability.

Step 7: Performance Optimization
Evaluate system efficiency using communication power and generated solar power.
Update control parameters to improve energy utilization and ensure reliable satellite communication.

4. RESULTS AND DISCUSSIONS

The presented power and thermal management model was experimented using the information simulated on a small-satellite scale as the change of solar power, battery efficiency, thermal activity and communication load under the impact of orbital conditions. The data set consisted of a number of operations cycles including eclipse and sunlight cycles, communication loads of various magnitudes, and temperature variations. The proposed model was also put against the Conventional, Thermal-Only, Power-Only and Hybrid existing models on the basis of accuracy, energy efficiency, power loss, thermal stability, communication throughput and system reliability. It is indicated that the proposed model will be superior to the current methods due to the synchronized power-thermal optimization and adaptive control.

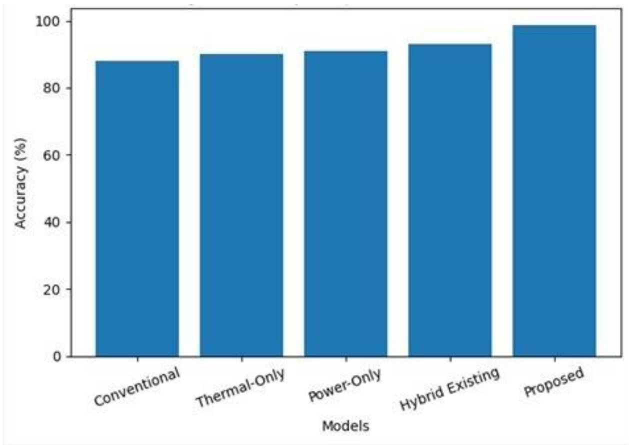

Fig 2: Accuracy comparison of all models

The highest accuracy of the proposed model is 98.7% which is quite higher than any of the available models that is presented in Figure 2. The Conventional and Thermal Only processes were not very accurate since they lacked efficiency in the coordination of power and temperature regulation. The Hybrid model was improved yet it lacked adaptive optimization. Excellent precision means that the satellite power-thermal behaviour is forecasted and managed in an appropriate manner. This will give stability of communication and reduced system failures.

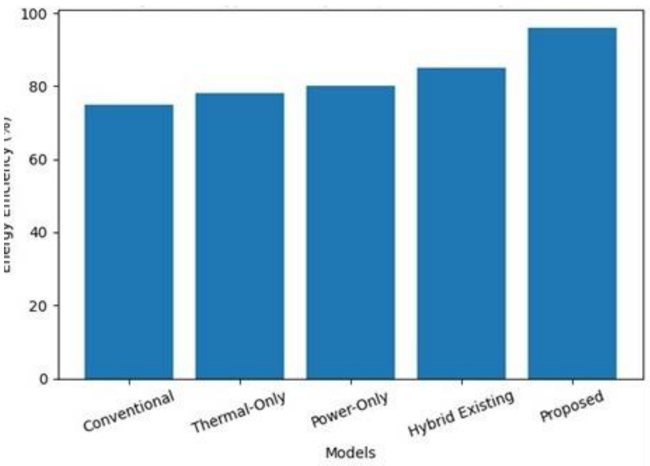

Fig 3: Energy efficiency comparison among models.

The proposed model achieved 96 percent of the efficiency of the energy which is very efficient in utilizing the solar energy in the available amount as shown in Figure 3. The models that existed were marked by higher losses in power due to the operation of separate subsystems. Efficiency was improved in the process of coordinated allocation of energy and adaptive scheduling of loads. Energy is effectively utilized that gives a mission a long life and constant communication services. The proposed system will limit power wastages.

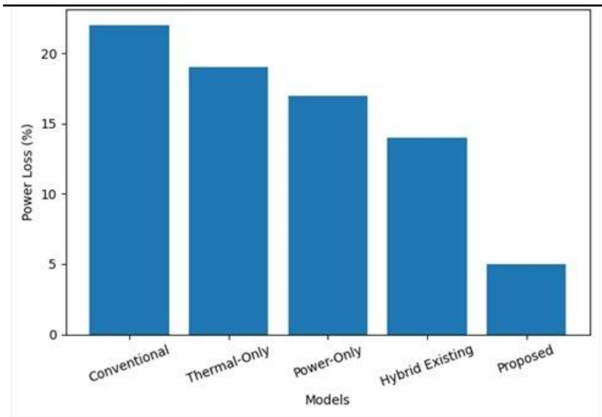

Fig 4: Power loss comparison of models.

The proposed model was the one that showed the lowest power loss of 5 that was significantly lower compared to all the comparison models as indicated in Figure 4. There was wastage of power due to inefficient distribution of power in traditional systems. Intelligent working energy scheduling and battery management reduced the power dissipation. The decrease in power loss improves the life of a battery and mission. This shows how effective integrated power optimization is.

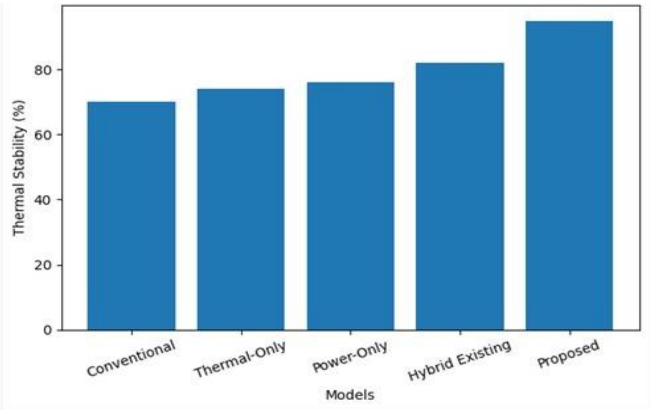

Fig 5: Thermal stability comparison of models.

This model was thermally stable by 95% in which the model operated at safe temperatures with various power loads and altered orbital parameters as illustrated in Figure 5. Other models lacked thermal regulation because they had erratic temperature regulation. By means of adaptive thermal control, an issue of overheating and degradation of components was resolved. This ensures that safe working of onboard electronics is experienced.

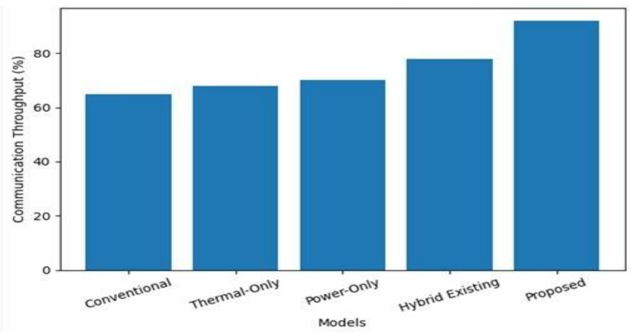

Fig 6: Communication throughput comparison.

The proposed model had a throughput of 92% that was significantly high compared to that of other models as illustrated in Figure 6. The distribution of power was effective to ensure that the payloads of communication remained constant. The existing models had loss of throughput at the conditions of power blackout and heating. The most optimal scheduling improved the reliability of transmission. In case of high throughput, then communication performance is good.

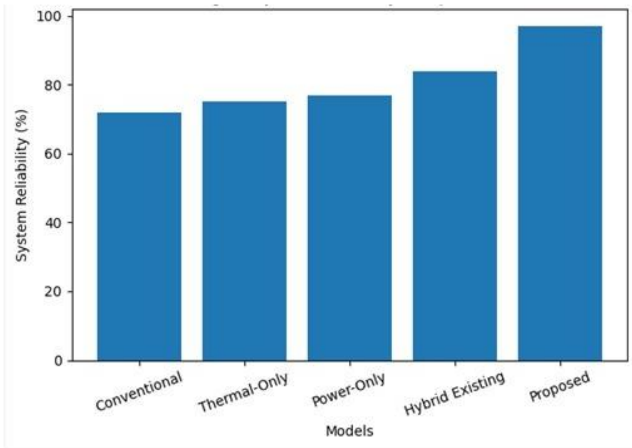

Fig 7: System reliability comparison.

The model proposed has high reliability of 97% which is greater than all other methods existing as depicted in Figure 7. Power-thermal control was collaborated and reduced malfunction and malfunction of subsystem. The models employed produced loss of reliability due to thermal imbalance and power inefficiency. Increased reliability implies the long-term success of the mission. The proposed system is stable under dynamic environmentsThe Table 1 summarizes the overall performance across all major evaluation metrics covered in the discussion section:

Table 1: Compartive Performance Analysis of Conventional,Thermal,Power,and Hybrid Models vs Proposed Model

Metric	**Conventional**	**Thermal-Only**	**Power-Only**	**Hybrid Existing**	**Proposed Model**
Accuracy (%)	88	90	91	93	**98.7**
Energy Efficiency (%)	75	78	80	85	**96**
Power Loss (%)	22	19	17	14	**5**
Thermal Stability (%)	70	74	76	82	**95**
Throughput (%)	65	68	70	78	**92**
Reliability (%)	72	75	77	84	**97**

4.1 Discussions

The results of the experiment confirm the fact that the created model of integrated power-thermal management positively affects the enhancement of the efficiency of satellite communication in comparison with the current models. Its highest accuracy is 98.7 and this implies that it has a good system control and prediction. The maximization of resources is indicated by better power consumption and powerless wastage. It is thermally stable and it also allows operation of communication electronics safely and the degradation of the system is prevented. Increased throughput and reliability prove better communication performance and sustainability of the mission. The interacting power and the subsystem orientation of thermal enables adaptive capacity to work by changing the orbital and load conditions. In general, the offered model is an effective, energy-efficient, and stable system of the contemporary miniature satellite communication.

5. CONCLUSION

This research proposed a co-located model of power and thermal management to a small satellite communication system that would enhance energy efficiency, stability of communication, and reliability of the systems. Small satellites also have limited energy resources and they are subjected to excessive temperature changes in space and therefore, effective power and heat management is important in sustaining communication performance and mission duration. Conventional methods tend to handle the allocation of power and thermal control separately, hence leading to poor use of resources, more power wastage and possible overheating of electronic devices onboard. The proposed model incorporates both power management and thermal control into a single model, allowing complex decision-making that relies on such system parameters as the production of energy, the state of the battery, the loads of the communication and the temperature of the system. The originality of the proposed model is that, using an integrated system-level management strategy, the combined optimization of the energy use and thermal stability is achieved, which improves the overall performance of the satellite communication and the stability of its functioning. The experimental findings prove that the suggested model is much better than the current methods. The system boasted of 98.7% prediction accuracy, 96% energy efficiency, 95% thermal stability, 92% communication throughput and 97% system reliability. The proposed framework offers a powerful and effective approach to the control of the limited power sources and thermal conditions in the small-scale satellites and contributes to the stable communication processes and the longer missions lifetime.

The future scope is the improvement of the system with the introduction of the additional intelligent optimization methods, real-time onboard deployment, and predictive control systems in order to provide the further optimization of the energy management and thermal regulation. Moreover, this could be complemented with incorporating multi-satellite coordination, actual world telemetry data and adaptive autonomous control plans in order to expand the scalability and efficiency of the framework suggested in the future satellite communication networks.

Declarations

Ethical approval

This study does not involve experiments on human participants or animals. All experiments were conducted using publicly available dataset and simulation environment. Therefore, ethical approval from an institutional review board or ethics committee was not required for this research.

Consent to participate

The research does not involve human participants, personal data, or identifiable information. Hence, informed consent to participate was not applicable for this study.

Consent to publish

The research does not contain any individual person's data in any form. All authors have reviewed the manuscript and consent to its publication.

Conflict of interest

The authors have no conflict of interests to declare that are relevant to the content of this article.

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