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Multi-Orbital Protection Schemes for Space-based Solar Power Systems

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***Abstract*—This Space solar power systems are recognized to be feasible sources of renewable energy. Their usefulness arises due to advances in satellite and space technology. However, the usefulness of space based solar power systems (and satellites) faces threats from the increased deployment of anti – satellite weapons and evolving Astro-politics. Therefore, there is need to design mechanisms to protect in–orbit space solar satellites. The research presented proposes a data deterrence approach and a novel multi–orbital mechanism for space solar satellites. The space solar satellites using the multi-orbital mechanism can switch to different orbits thereby making weapon target more difficult. Performance analysis shows that the use of the proposed multi – orbital approach enhances the accessible energy on average by 31% – 85%.**

Keywords—space solar power systems, anti–satellite systems, protection, dispatchable power.

I. Introduction

The need to achieve energy security is an important objective among developed and developing nations [1 – 2]. The realization of this goal has motivated the use of renewable energy sources. In this regard, the use of solar renewable energy [3], onshore renewable wind energy [4], and offshore renewable energy [5] has received considerable attention. Another approach that has received consideration is that of space based solar power systems [6 – 7, 8 – 9].

In a space-based power platform realized via a satellite, the energy is transmitted as an electromagnetic wave which is then converted to electrical energy on earth [10–14]. The derived electrical power can be harnessed and used in different applications. The use of space-based power platforms faces three different challenges. The first is that of energy transfer efficiency. This should be addressed due to the attenuation effect of clouds. The second is associated with the access of energy considering the occurrence of variability of accessing low earth orbiting space-based power platforms. The third arises due to the advances and expected future increase in the use of anti–satellite weapons. The need to consider this is because space based solar power systems can be deemed to have a power status.

For example, Space X's Starlink satellites provisioning drone navigation and communication related services to Ukrainian drones have been considered by Russia to have a weapon status [15]. In a similar manner, space based solar power systems can be deemed to have a weapon status when the energy derived is used to operate critical defense assets.

Therefore, it is important to design protection mechanisms for space based solar power systems. For example, developing countries are increasingly developing and deploying space assets for critical applications. From an astropolitical perspective, the space assets of countries can be deemed to be weapons due to existing alliances [16–17]. However, research has not significantly considered the space based solar power satellite as having a weapon status. It is considered important to address this security challenge.

Developing countries with limited resources also benefit from the use of space based solar power as this is a feasible solution for addressing energy insecurity. Therefore, deterrence enabling should be designed in this regard. The novelty and contribution of the research lies in its consideration of the space-based power platforms as having a weapon status. In addition, the influence of astro-politics and its ability to dynamically influence the weapon status of space-based power platforms is considered. The research contributions are:

- First, the research proposes a protection system for space based solar power platforms experiencing attacks from kinetic and directed energy weapons. The protection system emphasizes an increased monitoring of the payload launched into space. In the proposed architecture, the possibility of violating the existing outer space peace treaty should be considered. A cloud-based system that considers the sharing of more information to serve as a deterrence is proposed. In this case, the considered space based solar power platforms are located in the low earth orbit. Space based solar power systems experience attacks from kinetic and directed energy weapons.
- Second, the research proposes a novel orbital management mechanism for the launch of future space based solar power systems. The proposed orbital management introduces the concept of orbital switching capability. In the proposed orbital switching capability, the launched space based solar power system has the main, and the reserve orbits. The information on the orbital description and specification is not shared. The use of these orbits enables a satellite that has detected the presence of a weapon in its vicinity to move to an alternative orbit. This makes a successful weapon target harder to achieve as the satellite does not have a fixed orbit to which a weapon trajectory can lock as a fixed target.
- Third, the research proposes a network architecture which ensures that the occurrence of attacks on the space based solar power system does not lead to significant grid instability. The consideration in this context is appropriate in the case when attacks that are launched against space based solar power systems are successful.

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The rest of the discussed research is presented as follows: Section II focuses on the cloud based and data driven system. In this case, the proposed system and architecture introduces the sharing of more information to serve as a deterrence. This essentially presents a data driven deterrence. Section III presents the orbital management mechanism with a focus on space based solar power satellites and systems. Section IV presents the solution that minimizes the effect of successful attacks on the space based solar power satellite on the grid. Section V formulates the performance model demonstrating the influence of the proposed mechanisms on the power output. Section VI formulates the performance model.

II. Data Driven Detterence System

The proposed data driven deterrence system and architecture is herewith presented. In the system, an intending space services provider is required to present the details of the payload being launched and provided a statement of commitment to upholding the peaceful outer space treaty. Payload composition related information and not payload implementation is expected to be provided to a designated central authority. The required data is provided by the intended space service provider, and the launch services provider. Such an approach introduces the information elements of the payload composition for a given satellite identifier as required data to ensure conformance to the outer space treaty. Currently, the outer space treaty is passive manner and states are expected to commit to a peaceful use of space [18–20]. The existing approach in [18–20] is considered to be passive and the proposed data driven deterrence is active.

The realization of the data driven deterrence system considers data sovereignty. The consideration of data sovereignty is important due to the willingness of different countries and associated groups to share payload and mission related information with specific countries. The consideration of data sovereignty as regards the sharing of information is important for private organizations due to potential concerns on intellectual property. In the context of space based solar power systems, the information to be shared is intended to establish the weapon status of the satellite being launched.

The concerned information comprises the: (1) Functional Subsystem Description, (2) Surface area of the deployed onboard solar panel, (3) operational bandwidth, (3) maximum power output, (4) mean power output, and (6) minimum power output. Additional data that may be shared in a group include the: (1) Operational orbital altitude, (2) specifications of onboard defense technologies, and (3) locations of communication ground terminals.

The entity accessing the information i.e., the group with access to additional information or the non–group central authority analyses the weapon status of the space asset being launched. The analysis is done via a rule base hosting regulations on the weapon status designation or non- weapon status designation of the space asset before launch. The rule is derived as a consensus between public organizations and private organizations that deploy space assets for capability and service provisioning. The presence of loosely coupled kinetic elements or electromagnetic pulse generator is considered to increase the weapon status of a space asset. A deliberate refusal to provide the required data either to a central authority or a group makes a space asset to be classified as a space weapon.

The rule specification is dynamic i.e., the criteria can be updated with the emergence of new technologies and applications. The system architecture showing the data driven deterrence system is presented in Figure 1. In Figure 1, the information being accessed from the private and public organizations are those that describe the functionality of the concerned space asset's payload. Functional repositories that host information on satellite capability and identifier can be found earlier [21– 22].

The data accessed (as regards the components) from the private and public organizations is used in the rule consensus stage enabling the formation of the status designating rules. The rules are formed on the basis that the payload system, and component used in civilian satellite applications are known. This is feasible considering the significant maturity in satellite technology. The rule does not consider the payload components of space assets that have been clearly identified as being used in defense applications.

In Figure 1, the outcome of the rule consensus stage is the weapon status designation decision making algorithm. In this case, the decision-making algorithm considers the components used in the satellite being deployed by either the private or public organization. In a case where the hosted components do not conform to those enabling the realization of conventional application goals, the concerned satellite is considered non–civilian satellite.

The information obtained from the private organizations and the public organizations is the component of the payload for the space assets. In this case, the space asset is not limited to the proposed space based solar power application. The payload and component information is stored aboard a cloud platform and provided as input to the rule consensus stage.

In addition, a satellite that is deemed non – civilian satellite is further verified. The additional verification (indicated in the Further Verification Stage) enables the conduct of additional verification steps on the identified satellites. The verification stage involves making a request to the satellite operator as regards providing information enabling status designation

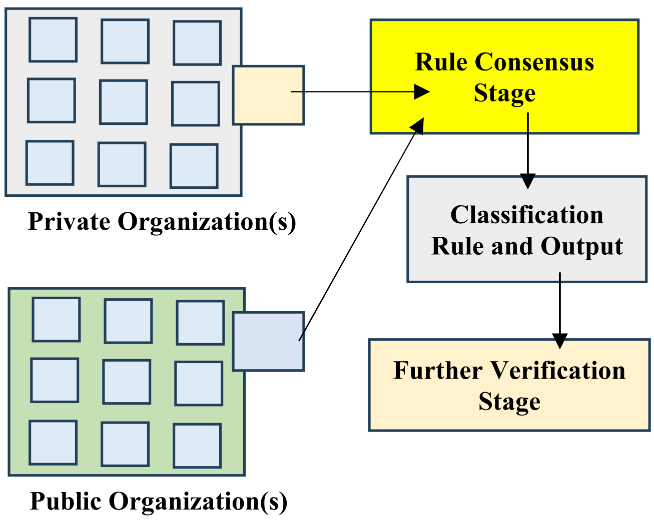

Fig. 1. Relations in the data deterrence system.

III. Orbital Management Mechanism

The design approach focuses on the online in–orbiting satellite. It presents the orbital management mechanism. The use of the orbital management mechanism is deemed to be most beneficial when malicious entities violate existing approaches to limit space weaponization. In the orbital management mechanism, a space-based power satellite is recognized to be conventionally hosted in a given orbit. This is the general and existing case associated with the orbital planning for satellite launch and application deployment. In this existing approach., the trajectory of the satellite can be easily predicted leading to the ability estimate the occurrence of collision with a launched anti–satellite kinetic energy weapon. An approach that makes it challenging to predict the trajectory of the satellite is proposed. It is more challenging to predict the applicable orbiting trajectory for a space based solar power satellite with multiple candidate trajectories. In this case, the use of more trajectories makes the execution of successful target more difficult.

The realization of orbital switching requires the use of intelligent orbit aware subsystems aboard the space based solar power satellite. In this regard, the required orbital transfer is executable via electric propulsion system aboard a small satellite as seen in [23 –25]. This requires the specification of alternative orbital trajectories and positions alongside the orbital switching sequence. The orbital switching sequence describes how long the space based solar power satellite spends in a given location. The configuration elements and the values of the alternative orbital trajectory, trajectory dwell duration, and trajectory switching sequence are not shared but their existence is made known. In orbital switching, the solar power satellite is launched into the main orbit. The transmission of power from the solar power satellite to the ground segment occurs when the solar power satellite is located in the main orbit. the space based solar power satellite transitions from the alternative orbital to the main orbital trajectory.

In addition, the execution of the orbital trajectory from the main orbital trajectory to the candidate orbital trajectories should consider collision minimization. Collision minimization refers to space observation as regards space debris passage or presence in the target alternative orbital trajectory. The orbital management mechanism comprises six stages. These stages are: (1) Main orbit trajectory specification, (2) Alternative trajectory specification, (3) Orbital Switching Sequence specification, (4) Alternative trajectory debris observation, (5) Initialization of communication, and (6) Switch to main orbit. In the orbital switching mechanism, a separating distance in the range of 400 km – 650 km is utilized to ensure high separation. Furthermore, satellites are often moving at high speeds in the range of tens of kilometers per second. In a case where the solar power satellite has a speed of 6.5 km per second, the orbital switching duration lies in the range 61.5 seconds–100 seconds.

The relations between these stages are presented in Figure 2. A solar power satellite executing the orbital switch is shown in Figure 3. In Figure 3, the solar satellite transits from the main orbital location to the alternative orbital location 1 in epoch t_1. The concerned solar satellite migrates from the alternative orbital location 1 to alternative orbital location 2 in the epoch t_2. In the return path, the migration from the alternative orbital location 2 to alternative orbital location 1 occurs at epoch t_3. In addition, the return to the main orbital location from the alternative orbital location 1 occurs at the epoch t_4. The system architecture shown in Figure 3 presents orbital switching for a single solar power satellite. However, the approach can be used for multiple single solar power satellite deployed in a constellation configuration. However, each of the space based solar power satellites have own alternative orbital locations.

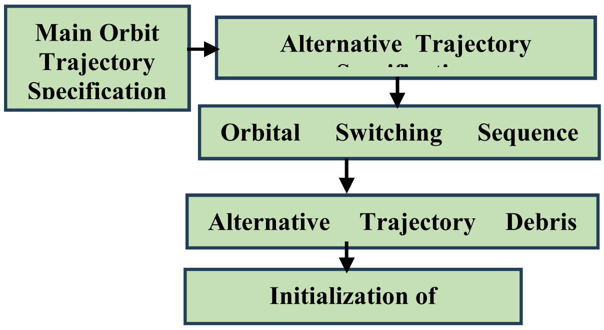

Fig. 2. Relations between the stages in orbital switching.

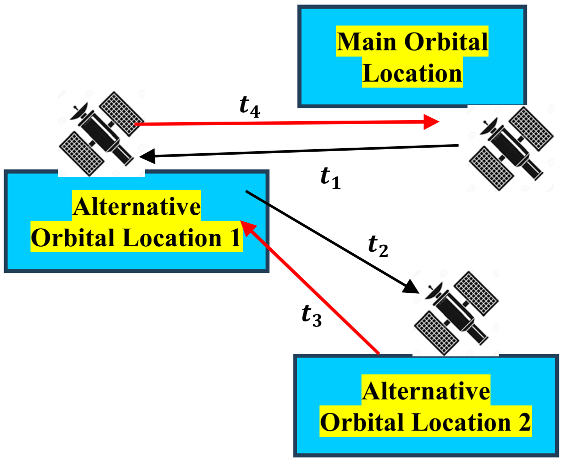

Fig. 3. Execution of the Proposed Orbital Switching.

IV. Integration into the Grid

The electrical power derived from the space based solar power is fed into a mini–grid and used within a larger grid system. A mini grid that feeds electricity into a larger grid is dedicated to the space based solar power constellation. The concerned mini grid receives solar power from multiple space based solar power satellites. Given a successful space-based weapon related attack, the power contribution from the dedicated mini–grid is reduced. The reduction in the power contribution results in the ability of the larger grid to overcome the fluctuations arising due to successful space weapon attacks.

An energy partition solution is proposed. In the proposed partition, a proportion of the energy accessed from the space based solar power satellite is stored. The other proportion of the energy accessed is fed into the larger grid system. The concerned storage is realized using battery arrays. An additional approach that is also used to increase the energy accessed from deployed space based solar power satellites is the use of multiple mini–grids. This increases the number of accessible power transmission windows. An increase in the number of accessible power transmission window implies that more energy is transferred from the constellation of space based solar power satellites. In this case the space based solar power satellite is in the main orbital location.

The use of an increased constellation size enables the realization of an increased power from the space based solar power satellite. The system showing the use of the energy partition for a single space solar satellite is presented in Figure 4. In Figure 4, the power reception entity in the earth-based station is realized via multiple ground stations. Each of the ground stations is connected to a power partition entity. The power partition entity sends a certain portion of the power to the battery pool in the reserve. The rest of the received power serves as input to the battery pool. Power in the battery pool is fed into the sub– grid where the power contribution drives the larger grid. The battery pool reserve engages in bi–directional communication with the reserve activation entity. The reserve activation entity receives data on the energy from the battery pool. This enables an activation of the use of the energy in the battery pool reserve.

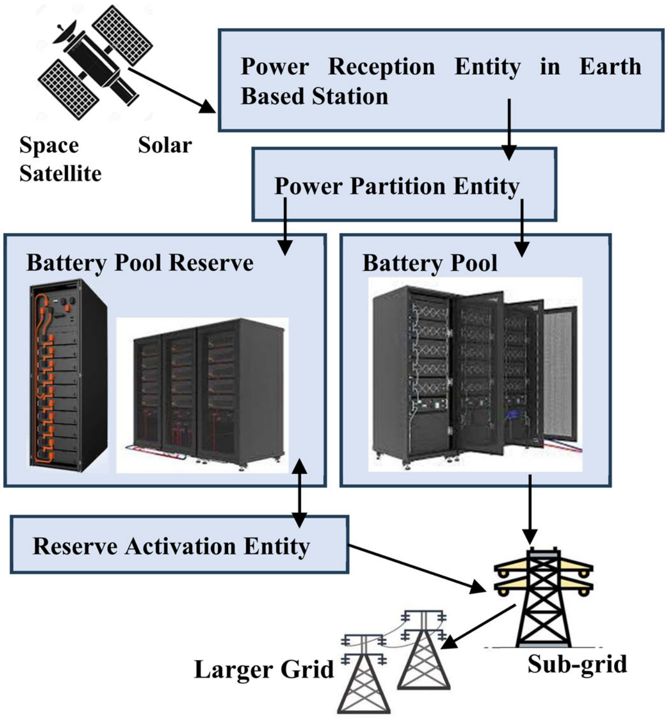

Fig. 4. Relations between solar satellite and the terrestrial grid.

V. Mathematical Formulation

The formulated performance metric is the accessible power derived from the use of the proposed approach. The formulation scenario is one considering the use of multiple solar power satellites and multiple ground stations i.e., power receivers. Let α and β, denote the set of solar power satellites and ground stations, respectively.

$$\alpha = \{\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_M\} \quad (1)$$

$$\beta = \{\beta_1, \beta_2, \beta_3, \ldots, \beta_N\} \quad (2)$$

In addition, the power derived from the m^{th} satellite $\alpha_m, \alpha_m \epsilon\, \alpha$ (via incident solar radiation) and received by the n^{th} ground station $\beta_n, \beta_n \epsilon\, \beta$ at the epoch $t_p, t_p \epsilon\, t, t = \{t_1, t_2, \ldots, t_P\}$ is denoted $P_1(\alpha_m, \beta_n, t_p)$. The parameter $P_1(\alpha_m, \beta_n, t_p)$ describes the power received at the power reception entity in the earth-based station β_n from the solar power satellite α_m at the epoch t_p. The proportion of the power fed into the battery pool reserve and the battery pool are $\gamma_1(\alpha_m, \beta_n)$, and $\gamma_2(\alpha_m, \beta_n)$, respectively. The attack indicator for the m^{th} satellite α_m is denoted $I(\alpha_m, t_p) \epsilon \{1,0\}$. The m^{th} satellite α_m experiences and does not experience an attack when $I(\alpha_m, t_p) = 1$, and $I(\alpha_m, t_p) = 0$, respectively.

The use of the orbital switch mechanism and capability motivates the introduction of the parameter describing the level of protection associated with the space based solar satellite. In this case, the protection related parameter for the m^{th} satellite α_m at the epoch t_p is denoted as $\theta(\alpha_m, t_p)$. A high value of the $\theta(\alpha_m, t_p)$ implies a high number of useful alternative orbital paths. A small value of $\theta(\alpha_m, t_p)$ implies a small number of useful alternative orbital paths. The output power before and after using the proposed mechanism is denoted Γ_1, and Γ_2, respectively.

$$\Gamma_1 = \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{p=1}^{P} P_1(\alpha_m, \beta_n, t_p) I(\alpha_m, t_p)\, \gamma_2(\alpha_m, \beta_n) \quad (3)$$

$$\Gamma_2 = \sum_{m=1}^{M}\sum_{n=1}^{N}\left(\sum_{p=1}^{(P-j)} P_1(\alpha_m, \beta_n, t_p)\, \theta(\alpha_m, t_p)\, \gamma_2(\alpha_m, \beta_n)\right) + \sum_{m=1}^{M}\sum_{n=1}^{N}\left(\sum_{p=(P-j+1)}^{P} P_1(\alpha_m, \beta_n, t_p)\theta(\alpha_m, t_p)\, \gamma_1(\alpha_m, \beta_n)\right) \quad (4)$$

The performance formulation in (3), and (4) consider the case where the solar power satellite transmits power to multiple ground stations. Furthermore, the relation in (3) presents the output power obtained in the existing case. The relation in (4) describes the output power obtained in the proposed case. In (4), the first term is the portion of the received power that is fed into the grid and derived from the battery pool. The portion of the received power that is fed into the grid and derived from the battery pool reserve is presented in the second term of (4).

VI. Performance Evaluation

The performance evaluation is done considering a scenario where there are multiple solar power satellites, and ground stations. In addition, it is assumed that the power received from the concerned solar power satellite is in the range of hundreds of Watts at a maximum of 0.15 kW. A conservative approach has been adopted in making this estimate and a high-power output is only achievable through the use of solar power satellite constellation, alongside multiple ground stations.

In the performance evaluation, analysis considers the existing approach, and the proposed approach. The existing approach is one in which satellites are used in the space based solar power application. In this case, the satellites are unable to execute the proposed orbital switching. This is the case with existing work as seen in [26]. In [26], the space based solar power system hosts satellites facing risk from space debris. However, an approach of orbital switching as proposed has

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not been incorporated in [26]. The existing approach is described by the solution proposed and presented in [26]. The proposed approach describes the case involving the use of the newly introduced orbital switching mechanism, and paradigm.

The simulation approach is used in investigating the performance benefits of the proposed approach. In addition, the simulation procedure shows that a small value of the protection parameter $\theta(\alpha_m, t_p)$ does not result in any meaningful performance benefit. This implies that the orbital trajectory switching mechanism is critical to ensuring that the adoption of the proposed approach results in significant performance benefits. In this case, the performance benefit is that of improving the power output and reducing energy security. In addition, the simulation also observes that the use of the proposed approach enables the satellite to have incidences to higher solar radiation since it moves between orbits.

The value protection parameter i.e., $\theta\left(\alpha_m, t_p\right)$ is considered from the perspective of that full solar power satellite protection is not achieved. Such an approach ensures that the scenario considers a non–ideal case and also incorporates the damaging influence of non–weapon space debris. The simulation parameters are presented in Table 1. The results obtained using the parameters in Table 1 is shown in Figure 6. An analysis of the results in Figure 5 shows that the use of the proposed approach enhances the total power output by an average of 31.7%. In addition, the results showing the variation of the mean protection parameter increases the accessible power is presented in Figure 6. The result shows that increasing the mean protection parameter enhances power output on average by (31 – 85) %.

TABLE I. SIMULATION PARAMETERS

S/N	Parameter	Value
	Existing Case	
1	Number of Solar Power Satellites (Entities)	40
2	Maximum Power Per Satellite (after incidence with solar radiation)	28.6 W
3	Minimum Power Per Satellite (after incidence with solar radiation)	936 mW
4	Mean Power Per Satellite (after incidence with solar radiation)	17.5 W
5	Maximum Value of Protection Parameter	3.4408
6	Minimum Value of Protection Parameter	0.0937
7	Mean Value of Protection Parameter	1.5593
8	Proportion of Damaged Satellites (existing case)	50%
9	Proportion of Non–Damaged (existing case)	50%

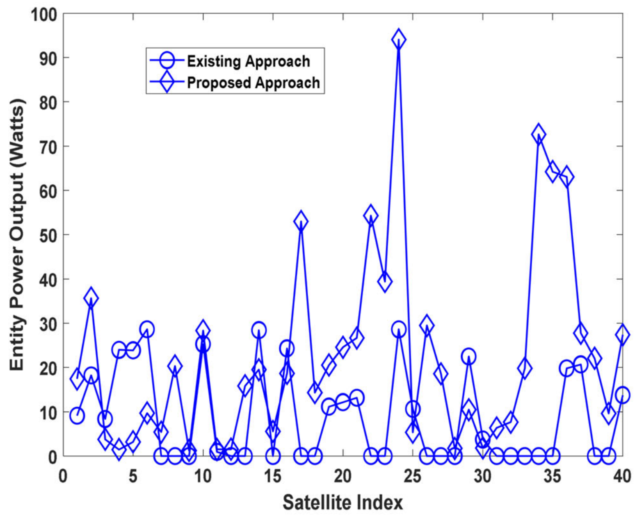

Fig. 5. Power Output (Watts) per entity.

VII. CONCLUSION

The results presented in the research study recognizes the maturation in space and satellite technology. The recognized maturation seeds the emergence of the application of deriving solar power for earth's use from space. In deriving solar power from space for use on earth, the space-based power satellite plays an important role.

The presented research recognizes that such space-based power satellites face significant threats from the launch and use of anti–satellite weapons. The concerned anti–satellite weapons are the kinetic anti–satellite, and the directed energy anti–satellite weapons..

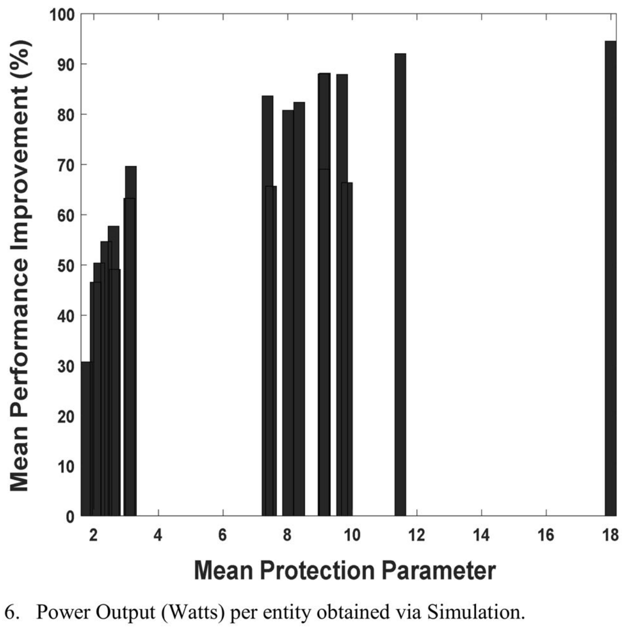

Fig. 6. Power Output (Watts) per entity obtained via Simulation.

The research study presented proposes, and discusses the use of data deterrence, and an enhanced orbital mechanism for reducing the effect of anti – satellite weapon attacks on the accessible power. Analysis shows that the use of the proposed mechanism enhances the power output by (31 – 85)% on average

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