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African Space Station(s) and the Power Problem

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Abstract— The occurrence of unfavorable meteorological conditions leads to the non-delivery of maximum power from space-based solar power systems. This leads to a case where the challenge of energy insecurity worsens and affects both civilian and non-civilian applications. Nevertheless, the space based solar power system approach is attractive because of its ability to provide power at any location due to the dynamic coverage of space based solar power satellites in the low earth segment. The research being proposed and presented advocates the use of a manned African Space Station with awareness of the meteorological condition to determine the epoch of transmission of power signal such that meteorological conditions do not result in total power absorption. In the proposed solution, manned crew aided by artificial intelligence executes multi-format information interpretation and inference alongside dynamic system reconfiguration. The research presents system architecture design for the use of the proposed approach in civilian and defense application contexts. Performance analysis shows that the use of the proposed approach enhances the accessible energy by an average of up to 67%, and 51% for civilian and defense application contexts, respectively.

Keywords – Space Systems; Power Access; Civilian Applications; Mobile Networks; Manned Space Stations ; Africa

I. INTRODUCTION

A considerable number of African nations face power security challenges. The high occurrence of power insecurity and instability has led to the non–realization of different national development goals. In addition, renewable energy systems are also being increasingly deployed in Africa as seen in [1–4]. However, the use of renewable energy sources has not resulted in a total elimination of the power insecurity challenge. This is due to the high costs associated with the adoption of renewable energy components such as solar panels, and wind turbines.

Advances in space technologies in different African nations is an important advancement that should also be considered. This is because of increasing advances in space technology. The use of space as a frontier for harnessing solar power has been recognized in [5–8]. In the existing approach, space based solar power involves the launch of unmanned spacecraft that radiates power from space i.e., the low earth orbit to earth-based power stations. The use of satellites i.e., space-based power nodes in this manner involves the transfer of electrical energy via microwave signals from space to earth. Ideally, the satellite i.e., space-based power node intercepts energy from incident solar radiation. The incident solar radiation is converted to electricity accessible on earth via the transmitted microwave radio signal. This is the case as seen in [9–10].

The current manner of transmitting electrical energy via microwave signals should consider events in space. In the existing approach, the space-based power node is unmanned and it is assumed that manned operations are not necessary. However, this is not so for all aspects of space related applications. For example, the international space station [11 – 12] and the Chinese space station [13–15] are manned space platforms being used for space research applications. These scientific applications benefit from human involvement to realize their goals. However, the use of human-guided autonomy capacity has not been examined in the framework of space based solar power. In the existing approach, the space-based power solar satellite transmits microwave energy to an earth-based ground station. The earth-based ground station is stationary and based at a given location. Being stationary, the energy signal being transmitted by meteorological conditions. The occurrence of meteorological conditions reduces the received energy when their presence causes signal absorption. The occurrence of signal absorption reduces the received energy. Therefore, the use of a stationary location for hosting the earth-based ground station does not lead to significant power reception.

The existing approach of using stationary earth-based ground stations for power reception in space based solar power systems results in three challenges as regards power output. These challenges are (i) Occurrence of cloud attenuation and cover results in signal (energy) absorption, (ii) Inefficient use of energy aboard satellite when high signal (energy) absorption occurs, and (iii) Reduced energy yield as stationary earth-based ground stations are not able to change locations to locations with reduced cloud cover, and signal (energy) absorption. These challenges arise because of satellite energy signal transmission is independent of cloud attenuation variation and observation; alongside the use of stationary earth-based ground stations in space-based satellite nodes.

Energy access is important to the crucial aspect of national defense, and for military applications. In military applications, energy access is required in regions without grid coverage. The energy access challenge becomes more significant when charged batteries are depleted and renewables are inaccessible. For example, solar radiation significantly reduces with low solar panel output during stormy weather. In such a scenario, the use of solar charged batteries by migrating military deployments becomes challenging.

Furthermore, the energy access in such a case (with poor grid coverage) becomes increasingly difficult due to the enormous challenge of adding wind turbines to the mobile defense payload. Therefore, a solution that enables energy access in scenario with depleted battery resources, stormy weather (with zero access to mobile wind turbines), low incident solar radiation, and non-grid access by mobile military deployments is required. The proposed research addresses these challenges and makes the following contributions :

1) First, the research proposes a mobile space-based solar power system. In the proposed mobile space-based solar power system, the ground segment comprises mobile ground segment for space-based solar power systems. The mobile ground segment comprises an earth-station that is capable of changing its location from an area with high cloud associated attenuation to one with low cloud associated attenuation. This migration enables the reception of stronger signal (higher power). The space segment comprises the manned African Space Station that transmits energy in variable communication windows. It

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receives information on the location of the mobile ground segment and transmits signal (energy) absorption in a manner that ensures reduced effect of cloud absorption.

2) Second, the research proposes and presents a networking architecture enabling the transmission of data related to cloud attenuation variation. The network architecture comprises the ground and space segment interacting via a communication network. In the proposed network, manned staff aboard the African Space Station communicates with the ground station before initiating signal (energy) transfer to the concerned location in the ground segment. The communication network comprises a terrestrial monitoring center that enables information exchange between the ground and space segment via the internet.
3) Third, the paper formulates, and investigates the performance metric for the use case of the proposed approach. The performance metric is formulated considering the received power given differing levels of cloud occlusion i.e., cloud attenuation on the received power level. In this existing case, the received power magnitude is significantly influenced by the occurrence of cloud absorption, and attenuation. The proposed case is one in which the novel approach is being used.

The rest of the research is organized as follows. Section II describes the problem being addressed. Section III presents the proposed solution. Section IV formulates the performance model. Section V discusses the results of performance evaluation. Section VI is the conclusion.

II. Problem Description

The scenario being considered is one in which a space based solar power system comprising space and ground segments has been deployed. The deployment is intended to be done with the aim of enhancing energy security. The space segment comprises multiple satellites used in the proposed space-based power system. The set of considered small satellites, and ground stations in the proposed scenario is denoted α, and β, respectively.

$$\alpha = \{\alpha_1, \alpha_2, \alpha_3, \dots, \alpha_I\} \quad (1)$$

$$\beta = \{\beta_1, \beta_2, \beta_3, \dots, \beta_J\} \quad (2)$$

The amount of power transmitted by the i^{th} satellite $\alpha_i, \alpha_i \in \alpha$ at the epoch $t_y, t_y \in t, t = \{t_1, \dots, t_Y\}$ is denoted as $P_1(\alpha_i, t_y)$. The amount of power received by the j^{th} ground station $\beta_j, \beta_j \in \beta$ at the epoch t_y is denoted as $P_1(\beta_j, t_y)$. A non-significant occurrence of cloud related occlusion and absorption affects the energy reception in the case given as:

$$\sum_{y=1}^{Z}\sum_{i=1}^{A} P_1(\alpha_i, t_y) \approx \sum_{y=1}^{Z}\sum_{i=1}^{A} P_1(\beta_j, t_y) \quad (3)$$

In (3), the case being considered is one in which the total power radiated by the satellites over the duration spanning epochs t_1 to t_Y is approximately equal to that which is received by the ground stations in a duration spanning the epochs t_1 to t_Y. The scenario presented in (3) is one in which the atmsophere's conditions do not significantly affect the amount of power received.

A challenge due to the occurrence of absorption in the atmosphere arises in the scenario described as:

$$\sum_{y=1}^{Z}\sum_{i=1}^{A} P_1(\alpha_i, t_y) \gg \sum_{y=1}^{Z}\sum_{i=1}^{A} P_1(\beta_j, t_y) \quad (4)$$

In (4), the energy radiated and transmitted by the satellites is significantly greater than the energy received by the ground stations over the duration spanning epochs t_1 to t_Y. Another scenario where the occurrence of cloud related absorption is existent and moderate is described as:

$$\sum_{y=1}^{Z}\sum_{i=1}^{A} P_1(\alpha_i, t_y) > \sum_{y=1}^{Z}\sum_{i=1}^{A} P_1(\beta_j, t_y) \quad (5)$$

The relation in (5) is one in which the cloud absorption and resulting attenuation does not result in the receipt of negligible energy at the earth station. A receipt of negligible energy at the earth station occurs in the scenario presented in (4).

In the event of the occurrence of a scenario in which (4) is valid requires a scenario in which (5) is valid. A solution that enables the realization of such a transition can be realized by ensuring that ground station moves from region where cloud attenuation and absorption associated with (5) to one where cloud attenuation and absorption is moderated as associated with (4). A solution that achieves this goal is presented and discussed in the presented research.

III. Proposed Solution

The discussion in this section presents the proposed solution i.e., the African Space Station and its supporting aspects. The African Space Station is being proposed as Africa's meaningful development of an application to benefit from space exploration. The proposed application is intended to address the challenge of power insecurity. The approach is deemed feasible due to recent advances in space technology, especially in the area of launch initiatives even in developing countries [16–19].

The solution being proposed is the use of a space station i.e., African Space Station in the space segment. The ground segment comprises the earth station that receives the power signal radiated from the space segment. The proposed solution does not use mobile earth stations in the ground segment. This is because of the high travelling velocity that is required to ensure that earth stations movement correspond to high satellite velocity.

The use of the proposed African Space Station provides a theme for Africa to participate in space exploration. The African Space Station is designed and launched to address the challenge of addressing power insecurity across different African countries. In its role, the African Space Station complements the electrical energy provided by existing power sources and systems. The rest of the discussion is divided into two aspects. The first aspect presents the role of the proposed African Space Station in providing energy for civilian applications. The second aspect discusses the role of the proposed African Space Station in the context of the providing power to mobile military deployment and applications.

A. System Integration – Civilian Focused Application

The proposed African Space Station is a manned system that is hosted in the low earth orbit. Its main purpose is to intercept solar radiation from space and transmit the energy signal to the earth station in the ground segment. The payload of the African Space Station comprises the following aspects (i) Power Subsystem, (ii) Computing Subsystem, (iii) Communication Subsystem, and (iv) Crew. The power subsystem's main components are the solar panels, and onboard battery. The computing subsystem hosts information on the amount of available onboard power, identities of earth stations (and locations) intended to receive the power signal,

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and information on system (African Space Station) health. The components of the communication subsystem are the onboard transceivers, and the antenna. In the manned African Space Station, the crew is a team of scientists, and engineers.

The communication subsystem receives information from the ground segment i.e., meteorological entity. The provided information hosts details on the level of cloud occlusion and absorption associated with the cloud cover in a given area. The concerned area hosts the earth station that receives the power signal from the African Space Station.

In the African Space Station low earth orbiting platform, the crew executes the following functions (i) Filling in gaps and making inference from multi-format meteorological data i.e., utilizing crew experience, (ii) Interpretation of multi-format received meteorological data to determine if power should be transmitted, and (iii) fixing computing subsystem related faults to ensure communication enabling transmission of power signal. In the power system comprising the African Space Station, the earth-station segment is integrated into the grid. This enables the earth station to provide electricity to meet end-user demand.

The use of significantly sized computing components is deemed necessary and cannot be supported aboard the conventional small satellite used in space based solar power applications. This is because of the need to store a significant amount of meteorological data aboard the computing subsystem. The stored data is used for decision making. In addition, the design of autonomous algorithms to execute the required analysis of multi-format data is deemed infeasible in a system with constraint on computing resources and capability. Moreover, the joint use of autonomous mechanisms, and human analytical capability occur in the African space station for improved data analysis and decision making.

The architecture of the African Space Station (space segment) is shown in Figure 1. Figure 1 shows the concerned subsystems i.e., power subsystem, computing subsystem, and communication subsystem being hosted within the domain of the crew chambers. Each of the crew members in the chamber can access any of the other subsystems. In Figure 1, the computing subsystem engages in bi-directional communication with the power subsystem, and communication subsystem. The bi-directional communication enables the communication system to send multi-format meteorological data to the computing system for processing. It also enables the computing subsystem to send a meteorological data request to the ground based meteorological agency via the communication subsystem. A bi-directional link between the computing subsystem and the power subsystem enables the computing subsystem to check how much power is available for transmission aboard the computing subsystem. The power subsystem also transmits operational status data to the computing subsystem on request for system state monitoring.

The proposed African space station transmits energy to a grid integrated earth station when the onboard meteorologist infers the non-existence of significant cloud occlusion. The energy is transmitted as microwave radio radiation at a high frequency of 8 GHz from the orbiting African space station. The microwave energy arising from the ASS is transmitted to a ground station i.e., the receiving antenna (rectenna). The rectenna is located in a quite zone. Being located in a radio quiet zone, the rectenna does not pose or experience interference threats. The rectenna is linked to a battery pool of nearby renewable energy farms.

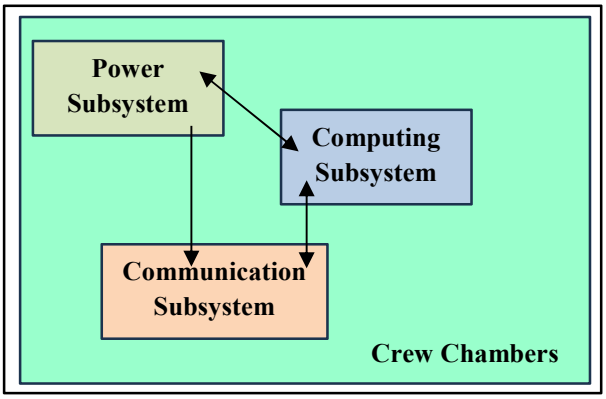


Figure 1: Architecture of the Proposed African Space Station.

The concerned battery pools are connected to grid-linked power conditioning systems. Prior to power reception, the earth station gains an awareness of future communication windows of the African Space Station. This enables the activation of the earth station for maximal power reception from the African Space Station. A scenario showing how multiple earth stations are connected to the grid is presented in Figure 2.

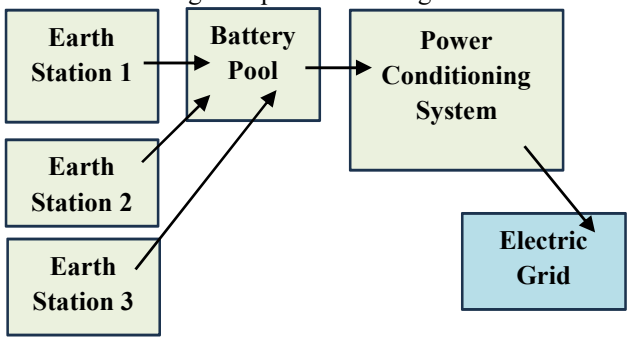


Figure 2: Connection of multiple earth stations (to the battery pool, power conditioning system and the electric grid.

B. System Integration – Defense Focused Application

The African Space Station is also able to provide to military forces deployed in various locations. In this case, defense forces utilize mobile and portable receivers to receive the microwave power signal. The transmission of the power (microwave) signal is done after the crew receives information on the occurrence of non-availability of grid coverage (and access), wind turbine and the occurrence of stormy weather.

The transmission of the microwave (i.e., power signal) is done at a higher frequency than in civilian integration. This is because of the improved portability of high frequency microwave (power) signal receivers. The transition of the operational frequencies is realized by including a software defined radio in the payload of the communication subsystem. The software defined radio ensures that the selected operational frequency does not pose risks to other spectrum accessing applications.

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The African Space Station gains an awareness of the location of the ground-segment military receiver via a location update. The location update is executed via communication between

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the in-field military team and the military coordination center. The military coordination center engages in information exchange with the manned crew aboard the African Space Station. In this way, the communication payload is reconfigured to transmit at the operational frequency of the concerned military deployment. The execution of the reconfiguration is followed by the transmission of the microwave (power) signal to the receiver. The relations between the entities associated with the execution of power transmission is shown in Figure 3.

The scenario in Figure 3 shows the relations between the transceiver, military coordination center (MCC), and the African Space Station. The bi-directional communication between the transceiver and the MCC enables the mobile military team to transmit signals informing the MCC of the location and the need for power. The MCC transmits information to the transceiver (mobile power receiver) on the scheduling of the communication i.e., details of the next available communication window from the African Space Station. The execution of bi-directional communication between the MCC between the African Space Station enables the MCC to transmit details of the transceiver to the manned crew aboard the African Space Station. The African Space Station transmits the commencement and completion of the communication to the concerned transceiver. The communication between the African Space Station and the transceiver only occurs on the downlink as the transceiver does not exchange information with the African Space Station.

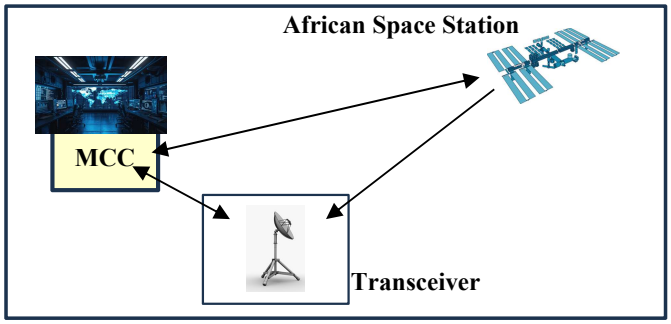


Figure 3: Relations between entities in defense integration case.

IV. Performance Formulation

The discussion in this section formulates the performance model for the proposed solution. The performance metric of interest is the accessible power in both civilian and defense contexts. In the existing case, the power transmitted by space based solar power satellites and similar payloads are affected by the occurrence of cloud absorption. This leads to the case where a proportion of the power transmitted does not reach the ground-based satellite power receiver. The role of the proportion of the power transmitted being absorbed is described by the cloud -power parameter (CPP). The CPP for the i^{th} satellite α_i at the epoch t_y,is denoted as $\gamma_1(\alpha_i, t_y)$. The use of the proposed approach i.e., the African Space Station leads to a case where the influence of the CPP i.e., the parameter $\gamma_1(\alpha_i, t_y)$ is reduced. The reduction in this case and which is associated with $\gamma_1(\alpha_i, t_y)$is described by the parameter $\gamma_2(\alpha_i, t_y)$.

In addition, it is also important to consider the incidence of solar radiation on the African Space Station's solar panels. The solar radiation incidence factor for the i^{th} satellite α_i at the epoch t_y is denoted $\theta_1(\alpha_i, t_y), 0 \leq \theta_1(\alpha_i, t_y) \leq 1$. In the formulation, a low value of $\theta_1(\alpha_i, t_y)$ indicates the occurrence of space events that reduce the magnitude of solar radiation that is incident on the African Space Station's solar panels. A high value of $\theta_1(\alpha_i, t_y)$ indicates the non-occurrence of space events that may reduce the magnitude of solar radiation aboard the African Space Station. The power accessible in the existing case is denoted P_1, and given as:

$$P_1 = \sum_{i=1}^{A}\sum_{y=1}^{Y} P_1(\alpha_i, t_y)\left(1 - \gamma_1(\alpha_i, t_y)\right)\theta_1(\alpha_i, t_y) \quad (6)$$

The power accessible in the proposed case is denoted P_2, and given as:

$$P_2 = \sum_{i=1}^{A}\sum_{y=1}^{Y}\prod_{p=1}^{2} P_1(\alpha_i, t_y)\theta_1(\alpha_i, t_y)\left(1 - \gamma_p(\alpha_i, t_y)\right) \quad (7)$$

In the defense application case, the set of receivers is denoted ς such that:

$$\varsigma = \{\varsigma_1, \varsigma_2, \ldots, \varsigma_Q\} \quad (8)$$

The accessibility of the q^{th} receiver $\varsigma_q, \varsigma_q \epsilon \varsigma$ to power sources at the epoch t_y is denoted $I_A(\varsigma_q, t_y)\epsilon\{1,0\}$. The receiver ς_q has access and does not have access to electrical power sources at the epoch t_y when $I_A(\varsigma_q, t_y) = 1$, and $I_A(\varsigma_q, t_y) = 0$, respectively. The initial amount of power aboard the q^{th} receiver ς_q is denoted $P_1(\varsigma_q, t_y)$. The amount of power accessible from accessible terrestrial power sources at the epoch t_y is denoted $P_{terr}(t_y)$. In addition, the amount of power accessible from the African Space Station at the epoch t_y is denoted $P_{space}(t_y)$.

The power resources aboard the satellite power receiver in existing case, and proposed case are denoted P_3, and P_4, respectively.

$$P_3 = \sum_{q=1}^{Q}\sum_{y=1}^{Y} P_1(\varsigma_q, t_y) + P_{terr}(t_y)I_A(\varsigma_q, t_y) \quad (9)$$

$$P_4 = \sum_{q=1}^{Q}\sum_{y=1}^{Y} P_1(\varsigma_q, t_y) + P_{terr}(t_y)I_A(\varsigma_q, t_y) + P_{space}(t_y) \quad (10)$$

V. Performance Evaluation

The performance evaluation procedure and parameters obtained via simulation for the civilian application case is presented in Table 1. The simulation parameters consider that there are 8 space power stations due to the paucity of capital resources within Africa. In addition, the maximum power that can be generated and stored aboard the space station is a maximum of 1 kW. This assumption has been made to limit the battery payload required for launching. In addition, the consideration of different values for the CPP parameter models a scenario comprising different meteorological conditions. In addition, the simulation and performance evaluation scenario consider a modest improvement in materials technology enhancing the power efficiency of solar panels being hosted aboard the space station. In this case, the improvement in efficiency is an average 67%. The results for the total accessible power obtained via performance evaluation in the civilian case are presented in Figure 4. The results in Figure 4 show that the proposed approach enhances the total accessible power.

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Table 1: Performance Evaluation Parameters (civilian case)

S/N	Parameter	Value
1	Number of Space Stations	8
2	Maximum Power in Space Station	841.9 W
3	Minimum Power in Space Station	350.2 W
4	Mean Power in Space Station	624.2 W
5	Maximum Cloud Power Parameter	87% %
6	Minimum Cloud Power Parameter	11.92 %
7	Mean Cloud Power Parameter	44.6 %
8	Maximum Reduction in Cloud Power Parameter	93.98 %
9	Minimum Reduction in Cloud Power Parameter	48 %
10	Mean Reduction in Cloud Power Parameter	64.51 %
11	Maximum Radiation Incidence Factor	0.9937
12	Minimum Radiation Incidence Factor	0.0638
13	Mean Radiation Incidence Factor	0.3584
14	Maximum Enhanced Radiation Incidence Factor	1.4591
15	Minimum Enhanced Radiation Incidence Factor	0.2083
16	Mean Enhanced Radiation Incidence Factor	0.8936

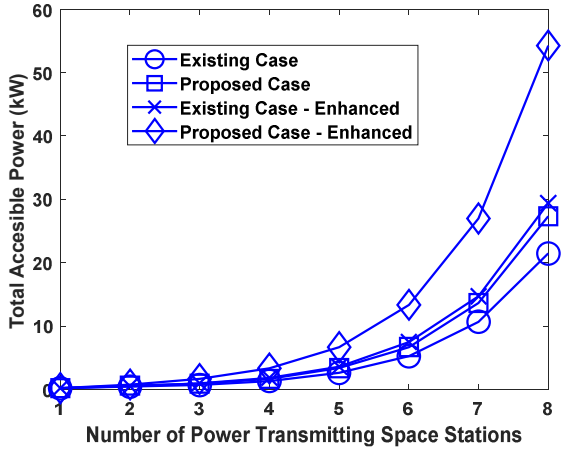


Figure 4 : Results of Total Accessible Power for the Civilian Application Case

Further analysis of the results shown in Figure 5 shows that the use of the proposed approach instead of the existing enhances the power output by an average of 25.5%. The use of solar panels with enhanced power efficiency aboard the proposed African Space Station also enhances the performance benefit of using the proposed approach. In this case, using the proposed approach instead of the existing approach increases the total accessible power by 67.4% on average.

The evaluation procedure also investigates the power accessible for the case of defense applications. In this case, the performance evaluation parameters are presented in Table 2. The power levels in Table 2 have been considered to be at the milliwatts level. This is deemed necessary to consider the occurrence of power losses in connectors associated with accessing power from the terrestrial and the proposed space solar power sources. In addition, a milliwatts power level is deemed appropriate as the simulation and evaluation procedure considers mobile devices with significant power limitation. The accessibility proportion describes the proportion of time for which a power source is accessible during the entire operational period.

The performance evaluation for the existing case and proposed case is shown in Figure 5. Furthermore, the results showing the power associated with the proposed case considering the introduction of the accessibility proportion of the space power sources is presented in Figure 6.

Table 2: Performance Evaluation Parameter (Defense Case).

S/N	Parameter	Value
1	Number of Receivers	10
2	Maximum Residual Receiver Power	29.7 mW
3	Minimum Residual Receiver Power	1.8 mW
4	Mean Residual Receiver Power	11.4 mW
5	Maximum Accessible Terrestrial Power	27.8 mW
6	Minimum Accessible Terrestrial Power	4.4 mW
7	Mean Accessible Terrestrial Power	17.4 mW
8	Maximum Accessible Space Power	33.8 mW
9	Minimum Accessible Space Power	4.5 mW
10	Mean Accessible Space Power	17.6 mW
11	Accessibility Proportion for Terrestrial Power Sources	50%
12	Accessibility Proportion for Space Power Sources	50%

The results of the performance evaluation in Figure 6 shows that the proposed case (without a consideration of the accessibility factor) enhances mobile device accessible power in comparison to the existing case. This is expected due to the introduction of the role of the African Space Station. Analysis shows that the use of the proposed approach enhances the device accessible power by an average of 51.4%. Further analysis also shows that the use of the proposed approach (with inclusion of accessibility factor) instead of the existing approach enhances the device accessible power by an average of 34.2%. Given the use of the proposed approach, the reduction of the accessibility factor by 50% reduces the device accessible power by an average of 17.2%.

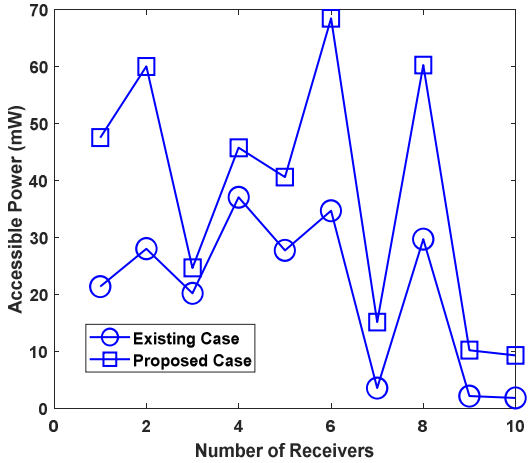


Figure 5 : Performance evaluation results for the accessible power (mW) in the defense application case.

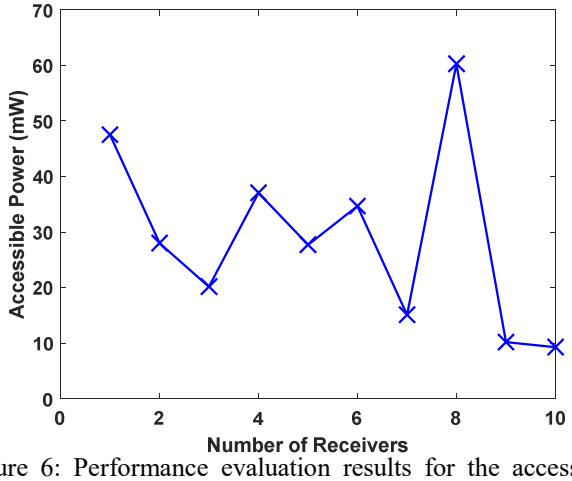


Figure 6: Performance evaluation results for the accessible power (mW) in the defense application case with focus on the proposed case (the space accessibility factor of 50%).

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VI. Conclusion

The use of space based solar power has significantly and recently received attention. The presented research addresses the case where energy sources from the terrestrial grid are inaccessible to civilian and defense applications. It is recognized that the use of space based solar power is beneficial due to its global and dynamic coverage. The benefits of global and dynamic coverage are applicable to platforms located in low earth orbit. The research recognizes the role that meteorological conditions play in the accessibility of electrical power from space based solar power platforms and proposes the use of future manned large scale solar power spacecraft. The proposed spacecraft, the African Space Station transmits power when meteorological conditions do not lead to significant absorption. The enabling reconfiguration driven by information inference is executed by onboard technical staff. Research presents the architecture of the system design for the manned African Space Station in civilian and defense applications. Analysis shows that the proposed application enhances accessible power by an average of 67%, and 51% for the civilian and defense applications, respectively. Future work considers how the design and launch of the proposed African Space Station alongside ground segment design influence the techno-economic analysis of the proposed approach.

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