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# Lunar Science: Internet for Space Tourism

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## Abstract

The increased interest in space exploration drives the development of novel technologies that are useful in other areas, such as aviation. The use of these technologies gives rise to new challenges and applications. Space tourism is an emerging application due to advances in space exploration technologies. This paper addresses two challenges aimed at ensuring continued internet access in space tourism. The first is designing network architecture to ensure continued internet access for space tourists aboard a space vehicle. The second is using aerial vehicle technology to enhance access to cloud content in areas with poor telecommunication infrastructure. The paper proposes the distributed handover algorithm ensuring that the space vehicle can execute handover from terrestrial wireless networks to aerial platforms and satellites as a last mile connection. It also proposes the concept of aerial diversity ensuring low cost access to cloud content. Performance simulation shows that the use of the distributed handover algorithm enhances channel capacity by 18.4% on average and reduces latency by 11.6% on average. The use of the cloud content access system incorporating aerial diversity enhances the channel capacity of terrestrial wireless networks by up to 85% on average.

**Keywords:** Space Tourism, Wireless Communications, Wireless Handover, aerial platforms, satellites, space tourist

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## 1. Introduction

The internet comprises multiple converging technologies that interact together in a global network. Information access via the internet faces a significant number of challenges. These challenges influence the ease with which information can be accessed via the internet. The quality of service (QoS) associated with internet access is determined by metrics such as channel capacity, latency, throughput and packet loss rate.

Advances in networking have played a significant role in internet evolution. For example, the internet initially used wired technology as the communication media; however, the internet is now accessed via wireless radio [1–3]. This transition increases the mobility of subscribers seeking to access data [4, 5]. The emergence of smartphones has improved subscriber ability to access the internet. This increased access requires network algorithms to support the realization of enhanced QoS in fifth generation (5G) wireless networks and beyond 5G (B5G) networks.

Internet access via wireless technologies benefits from new technologies such as: (i) new variants of the internet protocol (IP) and the transmission control protocol (TCP) [6–10], (ii) improved packet switching [11–13], (iii) World Wide Web [14], (iv) IEEE 802.11 wireless network standard [15], and (v) artificial intelligence [16, 17].

Currently, there is increased interest in space exploration leading to the development of technologies such as small satellites [18, 19] and aerial vehicles such as stratospheric platforms [19] and drones [20]. The development of these technologies enables capital constrained organizations to engage in space exploration. This also enables the emergence of new applications requiring internet access such as space tourism. The emergence of space tourism [21–39] requires a solution to providing uninterrupted internet access to subscribers aboard a space vehicle, as well as improving accessibility to the cloud content internet.

S/N	Acronym	Meaning
1	APSH	Aerial Platform to Satellite Handover
2	C-RAN	Cloud Radio Access Network
3	DHA	Distributed Handover Algorithm
4	eNB	Evolved Node B
5	gNB	Next generation Node B
6	MAV	Manned aerial vehicle
7	MIPv6	Mobile internet protocol version 6
8	P-GW	Packet data gateway
9	PMIPv6	Proxy mobile internet protocol version 6
10	QoS	Quality of Service
11	S-GW	Serving gateway
12	SMIPv6	Seamless mobile internet protocol version 6
13	SISH	Sub –orbital Intersatellite Handover
14	TCP	Transmission Control Protocol
15	TWAH	Terrestrial Wireless Network to Aerial Network Handover
16	TWNH	Terrestrial Wireless Network Handover
17	UAV	Unmanned Aerial Vehicle

Table 1. Acronyms used in this paper.

S/N	Parameter	Meaning
1	$N$	Set of wireless networks
2	$C$	Set of cloud platforms
3	$S$	Set of subscribers
4	$n_S$	Set of satellite networks
5	$n_T$	Set of terrestrial wireless networks
6	$n_S^r$	The $(r)^{th}$ satellite network.
7	$n_T^u$	The $u^{th}$ terrestrial wireless network
8	$C_i$	The $(i)^{th}$ cloud platform hosting content that subscriber $s_z$ seeks to access
9	$s_z$	The $(z)^{th}$ subscriber desiring access to cloud based content
10	$\alpha(n_T^u)$	The coverage region of $n_T^u$
11	$\alpha(n_S^r)$	The coverage region of $n_S^r$
12	$\beta$	Is the network sub – indicator
13	$I(\beta, C_i, t_j)$	Cloud access indicator at epoch $t_j$
14	$\emptyset$	Null set
15	$\theta$	Set of possible subscriber locations.
16	$\theta_g$	Set of ground locations for subscribers
17	$\theta_{ae}$	Set of aerial locations for subscribers
18	$\theta_g^c$	The $c^{th}$ ground location
19	$\theta_{ae}^n$	The $n^{th}$ aerial location
20	$N'$	Updated set of wireless networks
21	$\phi_{SU}$	the network designed to provide access to cloud content for $\theta_{su}$
22	$\mathbb{E}(s_x)$	Mean latency for subscriber $s_x$
23	$Th(s_x, \beta, t_j)$	Throughput associated with data accessed by $s_x$ ; $s_x \in S$ via network entity $\beta$ at epoch $t_j$
24	$D(s_x, t_j)$	Size of data accessed by $s_x$ from network entity $\beta$ at epoch $t_j$
25	$P_{th}(\gamma)$	Threshold signal strength for terrestrial wireless network base station entity.
26	$l_{th}$	Threshold Latency
27	$\mathbb{E}_1(s_z)$	The mean latency computed for multiple subscribers.
28	$\gamma$	Set of terrestrial wireless network base station entities
29	$\mathcal{P}$	Set of stratospheric platforms
30	$\mathcal{P}$	Set of satellites
31	$\kappa \in \{\gamma_b, \mathcal{P}_l, \mathcal{P}_t\}$	Entity $\kappa$ denotes transmitting nodes in terrestrial, stratosphere and outer space respectively.
32	$P(\kappa, t_j);$	The strength of the signal form entity $\kappa$ at epoch $t_j$
33	$C_{ter}$	Channel capacity of space vehicle in terrestrial plane
34	$C_{ae}$	Channel capacity of space vehicle in aerial plane
35	$C_{sp}$	Channel capacity of space vehicle in space plane.

S/N	Parameter	Meaning
36	$B(z', b)$	Bandwidth of channel $z'$ for the $b^{th}$ terrestrial wireless network base station entity
37	$B(z', l)$	Bandwidth of channel $z'$ for the $l^{th}$ stratospheric platform base station entity
38	$B(z', c)$	Bandwidth of channel $z'$ for the $c^{th}$ in – orbit satellite.
39	$P_{tr}(\gamma_d, z')$	Transmit power between the space vehicle and terrestrial wireless network $\gamma_d$ on channel $z'$
40	$P_{tr}(P_l, z')$	Data transmit power between the space vehicle and high altitude platform $P_l$ on channel $z'$
41	$P_{tr}(p_c, z')$	Data transmit power between the space vehicle and in – orbit satellite $p_c$ on channel $z'$
42	$P_{int}(\gamma_d, z')$	Interference power between the space vehicle and terrestrial wireless network on channel $z'$
43	$P_{int}(P_l, z')$	Interference power between the space vehicle and high altitude platform on channel $z'$
44	$P_{int}(p_c, z')$	Interference power between the space vehicle and in – orbit satellite on channel $z'$
45	$h_{11}(\gamma_d, z')$	Transmit channel gain between space vehicle and terrestrial wireless network on channel $z'$
46	$h_{11}(P_l, z')$	Transmit channel gain between the space vehicle and high altitude platform on channel $z'$
47	$h_{11}(p_c, z')$	Transmit channel gain between the space vehicle and in – orbit satellite on channel $z'$
48	$h_{12}(\gamma_d, z')$	Interference channel gain between space vehicle and terrestrial wireless network on channel $z'$
49	$h_{12}(P_l, z')$	Interference channel gain between the space vehicle and high altitude platform on channel $z'$
50	$h_{12}(p_c, z')$	Interference channel gain between the space vehicle and in – orbit satellite on channel $z'$
51	$C_{ave}$	Average channel capacity for the space vehicle
52	$I(\gamma_d, P_l)$	Handover indicator between $\gamma_d$ and $P_l$
53	$I(P_l, p_c)$	Handover indicator between $P_l$ and $p_c$
54	$D'$	Amount of transmitted data in bytes
55	$\beta_1$	Latency associated with data transmission in absence of proposed handover mechanism
56	$\beta_2$	Latency associated with data transmission after incorporating the handover mechanism
57	$P_{co}(\gamma_b)$	Probability of network congestion occurring on terrestrial wireless network $\gamma_b$
58	$Th(\gamma_b)$	Channel capacity of $\gamma_b$ is denoted $Th(\gamma_b)$
59	$Th_1^{cl}(\gamma_b)$	Aggregate channel capacity of accessing cloud content without proposed cyber – physical system
60	$Th_2^{cl}(\gamma_b)$	Aggregate channel capacity of accessing cloud content with proposed cyber – physical system

**Table 2.** Set of notations used in this paper.

This chapter addresses two challenges: it designs (i) a network infrastructure with associated mechanisms to ensure continued access for space tourist subscribers aboard a space vehicle and (ii) a solution to improve the cloud service accessibility in developing nations. The chapter makes the following contributions:

1. Firstly, it proposes a network architecture that incorporates the space tourist subscriber in commercial space flights. The space tourist subscriber requires access to cloud-based content and the proposed network architecture ensures that there is a continuity of access to cloud content at every tier via the proposed handover mechanism.

2. Secondly, it proposes a novel architecture that incorporates aerial diversity i.e. use of unmanned and manned aerial vehicles to achieve access to cloud content. This has the benefit of reducing congestion on in terrestrial wireless networks. The architecture uses manned and unmanned aerial and robotic entities for information delivery in the internet.
3. Thirdly, it formulates the performance metrics and benefits for the proposed mechanisms. These metrics are examined considering networks that do and do not incorporate the proposed mechanism. The metric is the aggregate throughput for a network comprising multiple base station entities.

The rest of the paper is structured as follows. Section 2 formulates the problem being addressed in this chapter. Section 3 presents the proposed mechanisms. Section 4 formulates the performance model. Section 5 presents and discusses the simulation results and performance benefits. Section 6 is the conclusion.

The list of acronyms and the set of notations used in this paper are shown in **Tables 1** and **2** respectively.

## 2. Problem formulation

The discussion here is divided into three parts. The first part describes the system model. The second defines the problem and challenges being addressed in this chapter. The third focuses on the challenge being addressed as regards access to cloud based services.

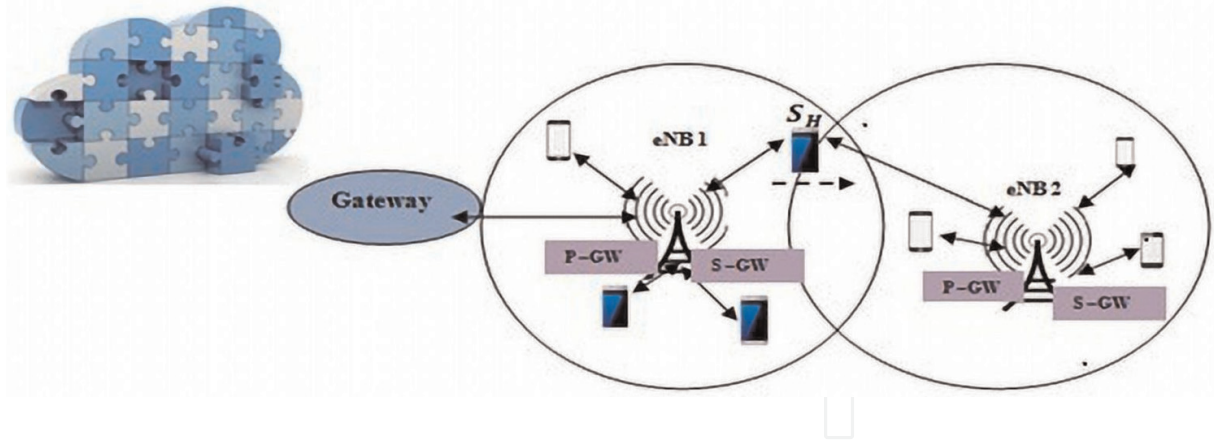
### 2.1. System model

The network scenario comprises cloud radio access networks (C-RANs). Each C-RAN comprises a base station entity such as the evolved Node B (eNB) or next generation Node B (gNB). The eNB or gNB is connected to a cloud platform that provides resources in the network control plane. The base station entity is connected to cloud platforms that host content being demanded by subscribers. The system model assumes that subscribers can access the network i.e. cloud content at the desired epoch. The network comprises terrestrial wireless and satellite network segments. A scenario showing the network is shown in **Figure 1**.

The scenario in **Figure 1** shows the connection between two eNBs (i.e. eNB1 and eNB2) with overlapping coverage. The first eNB i.e. eNB 1 is connected to the cloud platform being the closer of the two eNBs. The packet data gateway (P-GW) of eNB 1 interacts with the gateway entity at the cloud platform hosting the content being accessed. The eNBs can execute hand-over to support the migration of subscriber  $S_H$ . This is realized by the dynamics associated with serving gateway (S-GW) in seamless handover execution [40].

### 2.2 Problem definition: the 'space tourist' subscriber

The considered scenario comprises multiple networks enabling subscribers to access cloud-based content. Let  $N$ ,  $S$  and  $C$  be the set of wireless networks, subscribers and cloud platforms, respectively. Such as:



**Figure 1.** Network scenario showing the system model.

$$N = \{n_S, n_T\} \quad (1)$$

$$S = \{s_1, s_2, \dots, s_x\} \quad (2)$$

$$C = \{C_1, C_2, \dots, C_y\} \quad (3)$$

$$n_S = \{n_S^1, n_S^2, \dots, n_S^p\} \quad (4)$$

$$n_T = \{n_T^1, n_T^2, \dots, n_T^q\} \quad (5)$$

Where:

$n_S$  and  $n_T$  are the set of satellite and terrestrial wireless networks respectively.

$s_z, s_z \in S$  is the  $(z)^{th}$  subscriber desiring access to cloud-based content.

$n_S^r, n_S^r \in n_S$  is the  $(r)^{th}$  satellite network.

$n_T^u, n_T^u \in n_T$  is the  $(u)^{th}$  terrestrial wireless network.

$C_i, C_i \in C$  is the  $(i)^{th}$  cloud platform hosting content that subscriber  $s_z$  seeks to access.

The coverage region of  $n_T^u$  and  $n_S^r$  are denoted as  $\alpha(n_T^u)$  and  $\alpha(n_S^r)$ , respectively. Let  $I(\beta, C_i, t_j) \in \{0, 1\}, \beta \in \{n_T^u, n_S^r\}, t_j \in t, t = \{t_1, t_2, \dots, t_w\}$  be the cloud access indicator at epoch  $t_j$ . The states  $I(\beta = n_T^u, C_i, t_j) = 0$  and  $I(\beta = n_T^u, C_i, t_j) = 1$  signify that the  $(i)^{th}$  cloud platform  $C_i$  is inaccessible and accessible to base station entities of the  $(u)^{th}$  terrestrial wireless network at epoch  $t_j$  respectively. The indicator  $I(\beta = n_S^r, C_i, t_j) = 0$  and  $I(\beta = n_S^r, C_i, t_j) = 1$  signify that the  $(i)^{th}$  cloud platform  $C_i$  is inaccessible and accessible to base station entities of the  $(r)^{th}$  satellite network, respectively. The ground-based entity of the  $(r)^{th}$  satellite network is the terrestrial component of a satellite network.

A scenario described by the transition  $I(\beta = n_T^u, C_i, t_j) = 0, I(\beta = n_T^u, C_i, t_{j+1}) = 1, t_{j+1} \in t$  is one in which the cloud platform  $C_i$  is connected to network  $n_T^u$  at epoch  $t_{j+1}$  and not connected at



epoch  $t_j$  respectively. Another plausible scenario is  $(\beta = n_T^u, C_i, t_j) = 0, I(\beta = n_S^r, C_i, t_{j+1}) = 0, I(\beta = n_S^r, C_i, t_{j+j'}) = 0, t_{j+j'} \in t$ , which describes a case where subscriber  $s_z$  moves through the regions where access to cloud content via terrestrial network is infeasible at epochs  $t_j$  and  $t_{j+1}$  but feasible at epoch  $t_{j+j'}$ .

The variable  $I(\beta, C_i, t_j)$  can have a varying number of contexts described by transitions between different scenarios for different  $\beta, C_i$  and  $t_j$ . A common factor across these scenarios is the implied assumption that  $N \cap \{n_S \cup n_T\} \neq \emptyset$ . However, this does not consider the requirement to provide internet access in outer-space. Hence, another scenario that is yet to be considered is one described as  $N \cap \{n_S \cup n_T\} = \emptyset$  that considers the space tourist subscriber which has not been considered.

In the terrestrial plane, the subscriber  $s_z$  accesses the cloud content from a terrestrial location. However, cloud content can be accessed from other locations such as the ocean, and near space regions. Let  $\theta$  denote the set of possible subscriber locations, such as:

$$\theta = \{\theta_g, \theta_{ae}, \theta_{su}\} \quad (6)$$

$$\theta_g = \{\theta_g^1, \theta_g^2, \dots, \theta_g^v\} \quad (7)$$

$$\theta_{ae} = \{\theta_{ae}^1, \theta_{ae}^2, \dots, \theta_{ae}^m\} \quad (8)$$

$$\theta_{su} = \{\theta_{su}^1, \theta_{su}^2, \dots, \theta_{su}^f\} \quad (9)$$

Where

$\theta_g$  and  $\theta_{ae}$  are the set of ground and aerial locations respectively.

$\theta_g^c, \theta_g^c \in \theta_g$  is the  $c^{th}$  ground location.

$\theta_{ae}^n, \theta_{ae}^n \in \theta_{ae}$  is the  $n^{th}$  aerial location.

$\theta_{su}$  is the set of locations in space.

$\theta_{su}^{v'}, \theta_{su}^{v'} \in \theta_{su}$  is the  $v'$  sub-orbital location.

The definition of  $\theta$  excludes the underwater and underground locations.

There is coverage for locations  $\theta_g$  and  $\theta_{ae}$  given that  $I(\beta = n_T^u, C_i, t_j) = 1 \forall \theta_g, \theta_{ae}$  hold true. The condition  $I(\beta, C_i, t_j) = 1 \forall \theta_g, \theta_{ae}$  indicates that there is no network coverage for locations  $\theta_g$  and  $\theta_{ae}$ . Satellite and terrestrial wireless networks cannot deliver cloud access to space tourist subscribers when:

$$\{I(\beta = n_T^u, C_i, t_j), I(\beta = n_T^u, C_i, t_{j+1}), I(\beta = n_T^u, C_i, t_{j+j'}), \dots, I(\beta = n_T^u, C_i, t_w)\} = 0, \forall \theta_{su} \quad (10)$$

$$\{I(\beta = n_S^r, C_i, t_j), I(\beta = n_S^r, C_i, t_{j+1}), I(\beta = n_S^r, C_i, t_{j+j'}), \dots, I(\beta = n_T^u, C_i, t_w)\} = 0, \forall \theta_{su} \quad (11)$$



This is because terrestrial and satellite networks do not provide internet access for space tourist subscribers.

Let  $N'$  denote the set of updated set of wireless networks such that:

$$N' = \{N, \phi_{su}\} \quad (12)$$

Where  $\phi_{su}$  is the network designed to provide access to cloud content for  $\theta_{su}$ , then it is desired that:

$$\left\{ I((N' \cap N)', C_i, t_j), I((N' \cap N)', C_i, t_{j+1}), I((N' \cap N)', C_i, t_{j+j'}), \dots, I((N' \cap N)', C_i, t_w) \right\} = 0, \forall \theta_{su} \quad (13)$$

This paper designs a network architecture which ensures that (13) holds true at all epochs.

The discussion so far assumes that data access from the cloud in the contexts considered above is accompanied with a high QoS. This assumes the availability of reliable network infrastructure. For instance, this assumption is not true where exists poor availability of high-performance terrestrial network infrastructure, or subscribers' inability to access expensive satellite networks. This assumption is true for cloud service providers in nations with a high population demanding access to cloud content; described by the conditions:

$$\left\{ I(\beta = n_T^u, C_i, t_j), I(\beta = n_T^u, C_i, t_{j+1}), I(\beta = n_T^u, C_i, t_{j+j'}), \dots, I(\beta = n_T^u, C_i, t_w) \right\} = 0, \forall n_T, \theta_g \quad (14)$$

$$\left\{ I(\beta = n_S^r, C_i, t_j), I(\beta = n_S^r, C_i, t_{j+1}), I(\beta = n_S^r, C_i, t_{j+j'}), \dots, I(\beta = n_T^u, C_i, t_w) \right\} = 0, \forall n_S \quad (15)$$

If we let  $D(s_x, t_j)$  and  $Th(s_x, \beta, t_j)$ ,  $\beta \in \{n_T^u, n_S^r\}$  denote, respectively, the size of data accessed by  $s_x$  from network entity  $\beta$  and throughput associated with data accessed by  $s_x$ ;  $s_x \in S$  via network entity  $\beta$  at epoch  $t_j$ , then the mean latency  $\mathbb{E}(s_x)$  can be expressed as:

$$\mathbb{E}(s_x) = \frac{1}{2} \left( \frac{1}{wp} \sum_{j=1}^w \sum_{r=1}^p \frac{I(\beta = n_S^r, C_i, t_j) D(s_x, t_j)}{Th(s_x, \beta = n_S^r, t_j)} + \frac{1}{wq} \sum_{j=1}^w \sum_{u=1}^q \frac{I(\beta = n_T^u, C_i, t_j) D(s_x, t_j)}{Th(s_x, \beta = n_T^u, t_j)} \right) \quad (16)$$

Given the threshold latency  $l_{th}$ , the subscriber  $s_x$  has a significant delay if  $\mathbb{E}(s_x) \gg l_{th}$ . The delay  $\mathbb{E}(s_x)$  refers to that of a single subscriber. In the case of multiple subscribers, the latency  $\mathbb{E}_1(s_z)$  is given as:

$$\mathbb{E}_1(s_z) = \frac{1}{2} \left( \frac{1}{wpz} \sum_{j=1}^w \sum_{r=1}^p \sum_{z=1}^x \left( \frac{I(\beta = n_S^r, C_i, t_j) D(s_z, t_j)}{Th(s_x, n_S^r, t_j)} \right) + \ddot{Y}_1 \right) \quad (17)$$

$$\ddot{Y}_1 = \frac{1}{wpz} \sum_{j=1}^w \sum_{u=1}^q \sum_{z=1}^x \left( \frac{I(\beta = n_S^r, C_i, t_j) D(s_z, t_j)}{Th(s_x, n_S^r, t_j)} \right) \quad (18)$$

There is a significant degradation associated with accessing cloud-based content when  $\mathbb{E}_1(s_z) \gg l_{th}$ . Hence, a solution which ensures that the condition  $\mathbb{E}_1(s_z) \leq l_{th}$  holds true for a significantly long duration is required. Such a solution is proposed in this paper. This section presents the two challenges being addressed in this paper, namely:

1. Ensuring that space tourist subscribers engaged in sub-orbital space tourism flight have continued access to internet and cloud-based content. For example, space tourist subscribers should be able to upload content observed at high altitudes and in outer space to the cloud with low latency.
2. Designing a solution which ensures that the condition  $\mathbb{E}_1(s_z) \leq l_{th}$  holds true for subscribers desiring to access cloud-based content and for a significantly long duration.

### 3. Proposed solution(s) and associated mechanisms

This section presents the proposed solutions and is divided into two parts. The first part presents the solutions, mechanisms and associated network architecture to address the challenge involving space tourist subscribers. The second part discusses the solution that aims at ensuring the delivery of cloud-based content to subscribers at low latency when  $\mathbb{E}_1(s_z) \gg l_{th}$ .

#### 3.1. Internet access continuity in space tourism

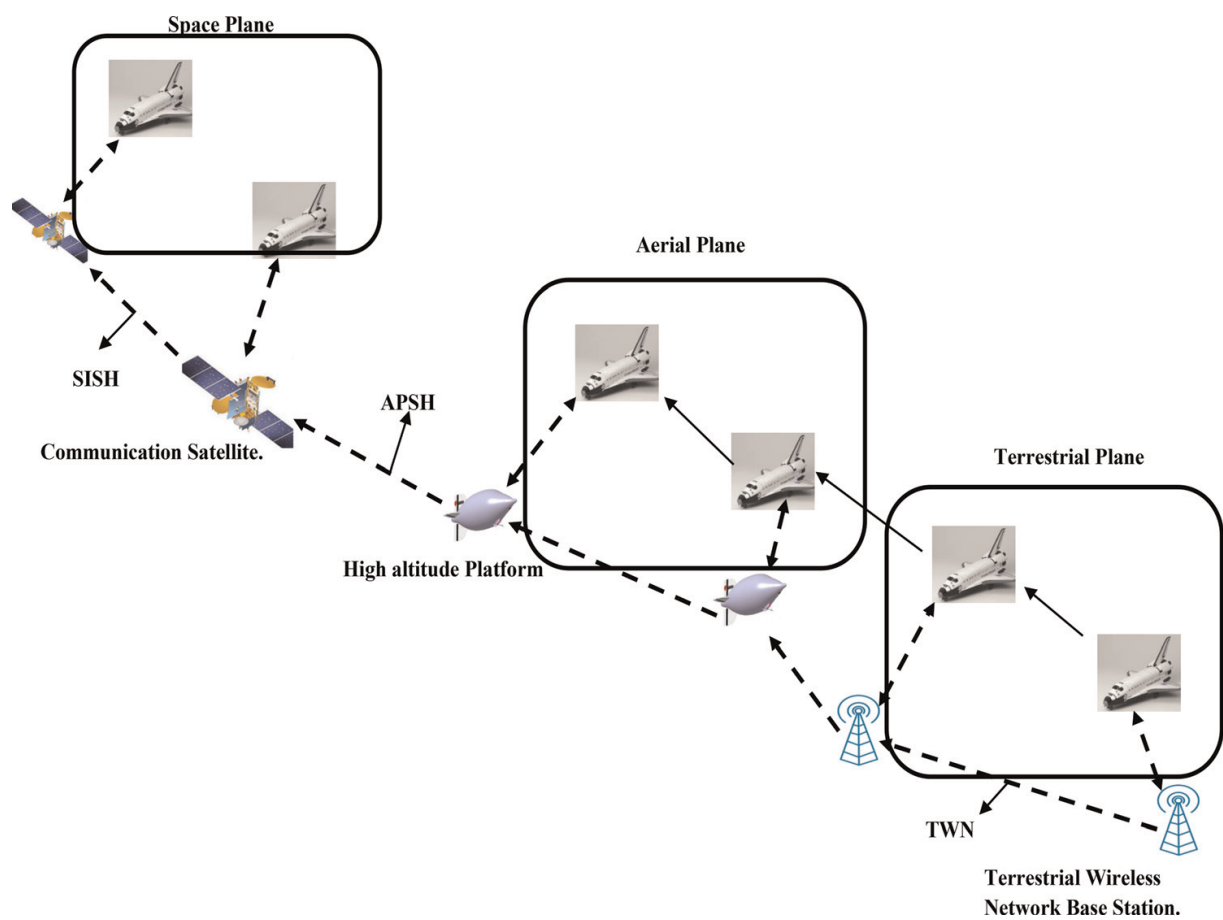
Space tourism subscribers are conveyed in a space vehicle that hosts communication subsystems which enables internet access. The space vehicle begins its journey from a terrestrial location with access to terrestrial wireless networks. The space tourists have access to the internet via the gateway of the terrestrial wireless network. In the context of the LTE-A utilizing the eNB, the P-GW and S-GW are the gateway entities. A handover is required to ensure the continuity of internet access as the space vehicle travels from the terrestrial location to outer space. Three handover levels are required in the proposed solution, these are:

1. **Terrestrial Wireless Network Handover (TWNH):** The TWNH refers to the handover executed between base station entities i.e. eNB. It is executed using protocols such as the seamless mobile internet protocol version 6 (SMIPv6) [41], mobile internet protocol version 6 (MIPv6) and proxy mobile internet protocol version 6 (PMIPv6) [42, 43]. The handover context implied in TWNH has been sufficiently addressed in literature.
2. **Terrestrial Wireless Network to Aerial Network Handover (TWAH):** The TWAH is necessary if the space vehicle connects to an aerial platform such as a high altitude platform as it sojourns to outer space. It involves the handover of a session from terrestrial wireless networks to aerial platforms. The aerial platforms in this context are connected using inter-platform links. Existing protocols such as that in [44] address the challenge of executing handover between terrestrial wireless networks and high altitude platforms.
3. **Aerial Platform to Satellite Handover (APSH):** The APSH involves executing a handover to the satellite on the uplink when subscribers access data from the cloud. The execution of

the APSH becomes necessary as the space vehicle’s altitude increases as it approaches low earth orbit. Existing approach consider that satellites should handover to stratospheric platforms in reaching the subscribers. The case here is different because the satellite network is in the last mile.

4. **Sub-orbital Intersatellite Handover (SISH):** The execution of the SISH is required to ensure that the in-orbit space vehicle connects to the satellite enabling it to have the highest throughput and lowest latency. The SISH redefines the role of satellites in accessing cloud based information via the internet. This is because inter-satellite links have often been used with the aim of achieving global coverage using satellite networks; and not in the context of providing seamless high QoS internet connections to subscribers as a last mile technology.

The space tourist subscriber requires internet access for obtaining content from the internet or storing content for storage and later access. This should be realized without significant space segment acquisition costs. The contexts implied in the APSH and SISH require novel mechanisms and accompanying network architecture. This is because the APSH and SISH phases are peculiar to the space tourist subscriber. The relations between the TWNH, TWAH, APSH and SISH are shown in **Figure 2**.



**Figure 2.** Relations between the TWNH, TWAH, APSH and SISH.

The scenario in **Figure 2** shows a space vehicle sojourning from a terrestrial location to outer space. The space vehicle passes through the terrestrial plane, aerial plane and the space plane. The space vehicle(s) is connected to the terrestrial wireless network base stations and access the cloud based content via the internet through the gateways. In the aerial plane, the space vehicle is connected to the high altitude platform.

The high altitude platform receives contents from select ground based stations. These ground stations are those being used for radio astronomy. However, they are not engaged in receiving radio astronomy signals during epoch of use by high altitude platform. The use of such ground stations is feasible considering the emergence of multi-mode ground stations that can be used for radio astronomy and packet processing [45]. The multi-mode ground station is connected to the computing infrastructure of the astronomy organization. The computing infrastructure is linked to the cloud computing platform hosting the content to be accessed by the space tourist subscriber. Idle multi-mode ground stations relay cloud based content to the space vehicle in the space plane. The cloud platform sends the cloud content to be sent to select ground stations that communicate with stratospheric platforms in the aerial plane. The select ground stations are also used to enable communications between satellites and the space vehicle in the space plane.

Aerial platforms communicate with each other using inter-platform links that utilize free space optics to ensure low latency. This is done when the space vehicle moves from the coverage of a high altitude platform to the coverage of another high altitude platform. In moving from the aerial plane to the space plane i.e. executing the APSH, the space vehicle does not have line of sight and communicates with the satellite via the ground station. In the space plane, the space vehicle is able to move between satellites. This is enabled by satellite communications with selected ground stations.

The proposed handover mechanism requires that the space vehicle conveying space tourists pass overhead through radio astronomy observatories. This provides the added benefit of enhancing astro-tourism and enables space tourists to have an aerial view of astronomical observatories. The re-use of existing astronomy infrastructure [46] reduces the cost associated with launching an anchor satellite to maintain high QoS internet connectivity for the concerned space vehicle. The use of selected ground station infrastructure improves the revenue potential for astronomy organizations; and increases the utilization of the high performance infrastructure and ground stations. The space vehicle connects to a geostationary communications satellite [47–51]. The ground segment of the geostationary satellite is an idle multi-mode ground station.

The handover algorithm that enables the provision of seamless internet connectivity for the space vehicle comprises entities that function in the space vehicle, ground stations, high altitude platforms and satellites. The proposed distributed handover algorithm (DHA) functions are for the aerial and space modes. The DHA executes the TWAH and the SISH in the aerial mode and space mode, respectively.

The space vehicle host mechanisms that enable it to execute the TWAH, and the handover between aerial platforms. However, these mechanisms are not designed since they have

received considerable research attention. Let  $\gamma$ ,  $\mathbb{P}$  and  $\mathbb{p}$  be the set of terrestrial wireless network base station entities, stratospheric platforms and satellites, respectively.

$$\gamma = \{\gamma_1, \gamma_2, \dots, \gamma_d\} \quad (19)$$

$$\mathbb{P} = \{\mathbb{P}_1, \mathbb{P}_2, \dots, \mathbb{P}_h\} \quad (20)$$

$$\mathbb{p} = \{p_1, p_2, \dots, p_n\} \quad (21)$$

In addition, let  $P(\kappa, t_j)$ ,  $\kappa \in \{\gamma_b, \mathbb{P}_l, p_t\}$ ,  $\gamma_b \in \gamma$ ;  $\mathbb{P}_l \in \mathbb{P}$ ;  $p_t \in \mathbb{p}$  denote the strength of the signal from entity  $\kappa$  at epoch  $t_j$ . Given that  $P_{th}(\gamma)$  is the threshold signal strength for terrestrial wireless network base station entity; the space vehicle measures the value of  $P(\kappa = \gamma_b, t_j)$  and  $P(\kappa = \mathbb{P}_l, t_j)$  and retains connectivity to the terrestrial wireless network if:

$$\frac{1}{dw} \sum_{b=1}^d \sum_{j=1}^w P(\kappa = \gamma_b, t_j) > P_{th}(\gamma) \quad (22)$$

$$\frac{1}{dw} \sum_{b=1}^d \sum_{j=1}^w P(\kappa = \gamma_b, t_j) > \frac{1}{hw} \sum_{l=1}^h \sum_{j=1}^w P(\kappa = \mathbb{P}_l, t_j) \quad (23)$$

If (22) does not hold true, then (23) is also invalid. The APSH should be executed if:

$$\frac{1}{hw} \sum_{l=1}^h \sum_{j=1}^w P(\kappa = \mathbb{P}_l, t_j) > P_{th}(\mathbb{P}) \quad (24)$$

$$\frac{1}{hw} \sum_{l=1}^h \sum_{j=1}^w P(\kappa = \mathbb{P}_l, t_j) > \frac{1}{hw} \sum_{b=1}^d \sum_{j=1}^w P(\kappa = \gamma_b, t_j) \quad (25)$$

The space vehicle is in the terrestrial plane if (22), (23) hold true and is in the aerial plane when (24), (25) holds true. The space vehicle moves from the aerial to the space plane if:

$$\ddot{\gamma}_1 < \ddot{\gamma}_2 < \ddot{\gamma}_3 \quad (26)$$

$$\ddot{\gamma}_1 = \frac{1}{h \times (j + j')} \sum_{l=1}^h \sum_{j=1}^{j+j'} P(\kappa = \mathbb{P}_l, t_j) \quad (27)$$

$$\ddot{\gamma}_2 = \frac{1}{h \times (\alpha')} \sum_{l=1}^h \sum_{j=j+j'+1}^{j+j'+\alpha'} P(\kappa = \mathbb{P}_l, t_j) \quad (28)$$

$$\ddot{\gamma}_3 = \frac{1}{h \times (w - (j + j' + \alpha' + 1))} \sum_{l=1}^h \sum_{j=j+j'+\alpha'+1}^w P(\kappa = \mathbb{P}_l, t_j) \quad (29)$$

The transition in (26)–(29) involves a movement of the space vehicle from the aerial plane to the space plane. This handover is executed in the APSH. A set of relations describing the



handover and the associated transition involving movement from the terrestrial plane to the aerial plane has not been presented. This kind of handover has been sufficiently addressed in the literature focused on aerial–terrestrial communications [45, 52, 53]. However, the context being addressed here is that of ensuring connectivity with a manned aerial vehicle (MAV) i.e. the space vehicle intended for space tourism.

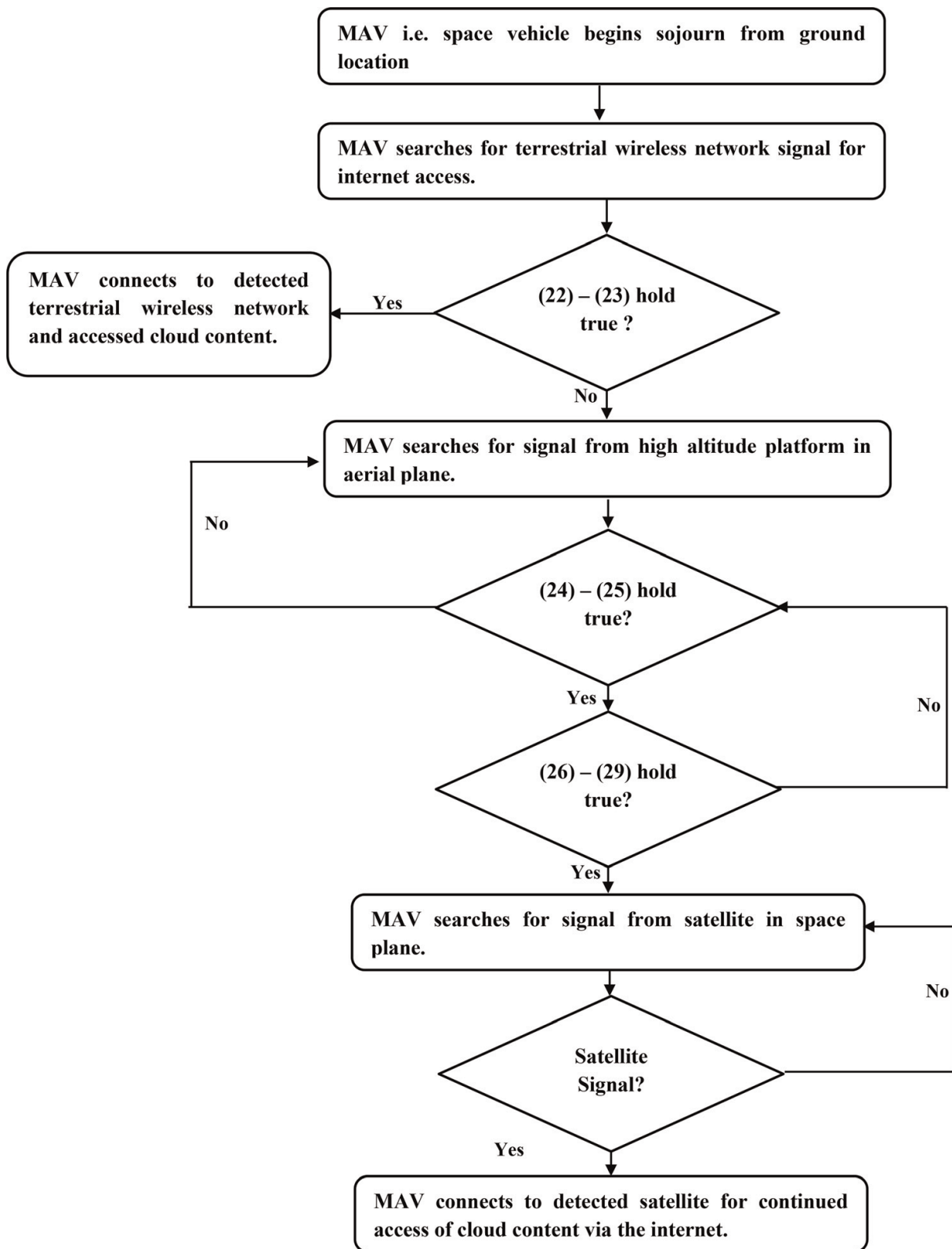
The handover and transition implied in the SISH becomes activated when  $P(\kappa = \mathbf{p}_l, t_j) < P(\kappa = \mathbf{p}_{l+1}, t_j); \mathbf{p}_{l+1} \in \mathbf{P}$  and the space vehicle selects satellite  $\mathbf{p}_{l+1}$ . The flowchart in **Figure 3** describes the relations executed in a handover procedure. The MAV searches for other networks of aerial platforms if the satellite signal is detected given that (26)–(29) holds true. In **Figure 3**, it is assumed that the space vehicle is able to connect to the concerned entities; i.e., high-altitude platforms or satellites depending on the decision context. The space vehicle connects to the entity with the highest transmit power.

### 3.2. Cyber: physical system - enhancing cloud access

The discussion presents a solution that enables subscribers to access cloud content when  $\mathbb{E}_1(s_z) \leq l_{th}$ . This scenario i.e.  $\mathbb{E}_1(s_z) \leq l_{th}$  describes one in which terrestrial subscribers cannot access cloud content at low latency. In a terrestrial wireless network, a high latency arises when there is network congestion or network overloading. The occurrence of network congestion results in a low aggregate throughput in the network segment as well as a high latency. Existing research has considered the use of unmanned aerial vehicles to enhance the capacity of existing terrestrial wireless networks in several contexts [40, 41, 44]. Hence, unmanned aerial vehicles are suitable for addressing the challenge by providing an alternative path for accessing cloud content. Hence, unmanned aerial vehicles provide a cyber-physical extension (window) into the cloud platform. The proposed cyber-physical cloud comprises a central cloud platform or data center with several cloud extensions (windows). The use of the cyber-physical cloud also enhances the ability of space tourists to access cloud content. In this case, the space tourist is in the terrestrial plane when the condition  $\mathbb{E}_1(s_z) \leq l_{th}$  is observed to hold true. Hence, the proposed cyber-physical cloud access system also enhances the provision of cloud based content to the internet.

In the cyber-physical cloud, the central cloud platform connects to the terrestrial wireless network and the cyber-physical windows as shown in **Figure 4**. In **Figure 4**, the cloud connects to either the aerial vehicle or the terrestrial wireless network. The subscribers desiring access to cloud based content are connected to the base station or the aerial vehicle. In the event that  $\mathbb{E}_1(s_z) \gg l_{th}$ , the notification is sent to the cloud and aerial vehicles are deployed.

The condition  $\mathbb{E}_1(s_z) \gg l_{th}$  is verified at the cloud platform using information on the latency associated with data reception by each individual desiring access to cloud content. Each subscriber receiving content from the cloud via own terminals send information on the latency associated with content reception to the cloud platform. The usage of the term aerial vehicle implies both manned aerial vehicles (MAVs) and unmanned aerial vehicles (UAVs). The joint usage differs from the approach where only UAVs are used in the system [54].



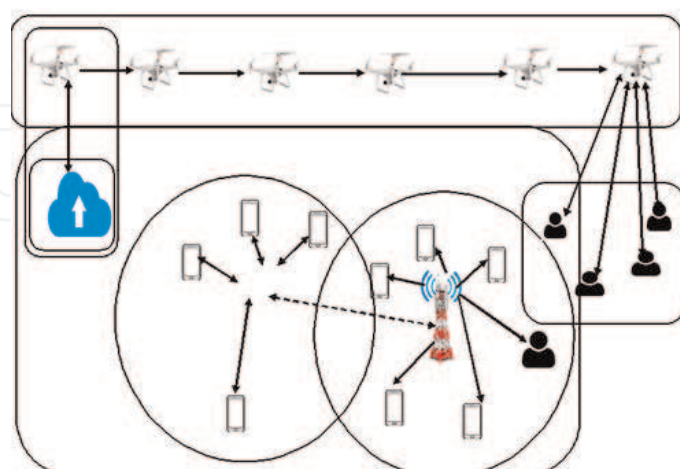
**Figure 3.** Functional flowchart showing the execution of the proposed handover for the space vehicle i.e. MAV.



The sole use of UAVs in the absence of aerial diversity does not consider regional aviation safety concerns. The incorporation of MAVs with UAVs enables the use of aerial vehicles in a manner that meets aviation safety concerns. For example MAVs are human driven and can be used in areas with constraints on aviation safety. The MAV is an aerial vehicle with smaller dimensions than the conventional manned aircraft; it is equipped with a communication payload that enables data communication with the cloud platform.

In the cyber-physical cloud, the central cloud platform connects to the terrestrial wireless network and the cyber-physical windows as shown in **Figure 4**. In **Figure 4**, the cloud can connect to either the aerial vehicle or the terrestrial wireless network. The subscribers desiring access to cloud-based content are connected to the base station or the aerial vehicle. In the event that  $\mathbb{E}_1(s_z) > l_{th}$ , the notification is sent to the cloud and aerial vehicles are deployed.

The condition  $\mathbb{E}_1(s_z) > l_{th}$  is verified at the cloud platform using the information on the latency associated with data reception by each individual desiring access to cloud content. Each subscriber receiving content from the cloud via own terminals sends information on the latency associated with content reception to the cloud platform. The usage of the term aerial vehicle implies both MAVs and UAVs. The joint usage differs from the approach where only UAVs are used in the system [54]. The sole use of UAVs in the absence of aerial diversity does not consider stringent regional aviation safety concerns. The incorporation of MAVs with UAVs enables the use of aerial vehicles in a manner that meets stringent aviation safety concerns. For example, MAVs are human driven and can be used in areas with stringent constraints on aviation safety. The MAV is an aerial vehicle with smaller dimensions than conventional manned aircraft. It is equipped with a communication payload that enables data communication with the cloud platform.



**Figure 4.** Incorporation of MAV and UAV into enabling cloud access.

## 4. Performance modeling and formulation

This section focuses on formulating the performance model of the proposed mechanisms. It is divided into two parts. The first part formulates the performance metrics of the mechanism enabling the internet access in space tourist applications. The second part formulates the performance analysis for the cyber-physical cloud system incorporating aerial diversity.

### 4.1. Performance model: space tourist enabling mechanism

The formulated QoS metrics are the channel capacity and latency. The channel capacity for the space vehicle is formulated considering cases where the proposed handover mechanism is used and not used. The channel capacity achievable by the space vehicle in the terrestrial plane, aerial plane and space plane are denoted as  $C_{ter}$ ,  $C_{ae}$  and  $C_{sp}$  respectively and can be expressed as:

$$C_{ter} = \sum_{z'=1}^{z'} \sum_{b=1}^d B(z', b) \log_2 \left( 1 + \frac{P_{tr}(\gamma_b, z') |h_{11}(\gamma_b, z')|^2}{P_{int}(\gamma_b, z') |h_{12}(\gamma_b, z')|^2 + \sigma^2} \right) \quad (30)$$

$$C_{ae} = \sum_{z'=1}^{z'} \sum_{l=1}^h B(z', l) \log_2 \left( 1 + \frac{P_{tr}(\mathbf{p}_l, z') |h_{11}(\mathbf{p}_l, z')|^2}{P_{int}(\mathbf{p}_l, z') |h_{12}(\mathbf{p}_l, z')|^2 + \sigma^2} \right) \quad (31)$$

$$C_{sp} = \sum_{z'=1}^{z'} \sum_{c=1}^n B(z', c) \log_2 \left( 1 + \frac{P_{tr}(\mathbf{p}_c, z') |h_{11}(\mathbf{p}_c, z')|^2}{P_{int}(\mathbf{p}_c, z') |h_{12}(\mathbf{p}_c, z')|^2 + \sigma^2} \right); \mathbf{p}_c \in \mathbf{p} \quad (32)$$

Where:

$z'$  is the channel  $z'$  which is distinct for each concerned communication entity.

$P_{tr}(\gamma_d, z')$ ,  $P_{tr}(\mathbf{p}_l, z')$  and  $P_{tr}(\mathbf{p}_c, z')$  are the operational data transmit power between the space vehicle and (i) terrestrial wireless network on channel  $z'$ , (ii) high altitude platform on channel  $z'$  and (iii) communication satellite on channel  $z'$  respectively.

$P_{int}(\gamma_d, z')$ ,  $P_{int}(\mathbf{p}_l, z')$  and  $P_{int}(\mathbf{p}_c, z')$  is the interference power between the space vehicle and (i) terrestrial wireless network on channel  $z'$ , (ii) high altitude platform on channel  $z'$  and (iii) communication satellite on channel  $z'$  respectively.

$h_{11}(\gamma_d, z')$ ,  $h_{11}(\mathbf{p}_l, z')$  and  $h_{11}(\mathbf{p}_c, z')$  are the transmit channel gain between the space vehicle and (i) terrestrial wireless network on channel  $z'$ , (ii) high altitude platform on channel  $z'$  and (iii) communication satellite on channel  $z'$  respectively.

$h_{12}(\gamma_d, z')$ ,  $h_{12}(\mathbf{p}_l, z')$  and  $h_{12}(\mathbf{p}_c, z')$  are the transmit channel gain between the space vehicle and (i) terrestrial wireless network on channel  $z'$ , (ii) high altitude platform on channel  $z'$  and (iii) communication satellite on channel  $z'$  respectively.

The average channel capacity of the space vehicle is denoted as  $C_{ave}$  and given as:

$$C_{ave} = \frac{1}{3} (C_{ter} + I(\gamma_d, \mathbf{p}_l) C_{ae} + I(\mathbf{p}_l, \mathbf{p}_c) C_{sp}) \quad (33)$$

Where:

$I(\gamma_d, \mathbf{p}_l) \in \{0, 1\}$  is the handover indicator between  $\gamma_d$  and  $\mathbf{p}_l$ . The cases  $I(\gamma_d, \mathbf{p}_l) = 0$  and  $I(\gamma_d, \mathbf{p}_l) = 1$  signify that a handover is not executed and is executed between  $\gamma_d$  and  $\mathbf{p}_l$  respectively.

$I(\mathbf{p}_l, \mathbf{p}_c) \in \{0, 1\}$  is the handover indicator between  $\mathbf{p}_l$  and  $\mathbf{p}_c$ . The cases  $I(\mathbf{p}_l, \mathbf{p}_c) = 0$  and  $I(\mathbf{p}_l, \mathbf{p}_c) = 1$  signify that a handover is not executed and is executed between  $\mathbf{p}_l$  and  $\mathbf{p}_c$  respectively.

The latency associated with transmitting  $D'$  bytes of data without and with the incorporation of the proposed handover is denoted  $\beta_1$  and  $\beta_2$  respectively and given as:

$$\beta_1 = 8 \times D' \times (C_{ave})^{-1} \Big|_{I(\gamma_d, \mathbf{p}_l)=0, I(\mathbf{p}_l, \mathbf{p}_c)=0} \quad (34)$$

$$\beta_2 = 8 \times D' \times (C_{ave})^{-1} \Big|_{I(\gamma_d, \mathbf{p}_l)=1, I(\mathbf{p}_l, \mathbf{p}_c)=1} \quad (35)$$

The cases  $8 \times D' \times (C_{ave})^{-1} \Big|_{I(\gamma_d, \mathbf{p}_l)=1, I(\mathbf{p}_l, \mathbf{p}_c)=0}$  and  $8 \times D' \times (C_{ave})^{-1} \Big|_{I(\gamma_d, \mathbf{p}_l)=0, I(\mathbf{p}_l, \mathbf{p}_c)=1}$  have not been considered. This is because our discussion does not consider a partial handover as implied in the cases described by  $I(\gamma_d, \mathbf{p}_l) = 1, I(\mathbf{p}_l, \mathbf{p}_c) = 0$  and  $I(\gamma_d, \mathbf{p}_l) = 1, I(\mathbf{p}_l, \mathbf{p}_c) = 1$ . A partial handover results in a scenario where QoS of the space tourist subscribers suffer severe degradation due to frequent interruption.

#### 4.2. Performance model: cyber-physical aided cloud access system

The deployment of either the UAV or MAV in the proposed cyber-physical cloud access system enables the delivery of cloud content when it could otherwise be challenging. This is due to the incidence of network congestion or any other event that could lead to high delay in the terrestrial wireless network segment. In the formulation, the cloud content traverses multiple cells in an infrastructure-based network. The occurrence of congestion on any of the forwarding network nodes increase the latency associated with accessing cloud content by remote subscribers. The probability of congestion on terrestrial wireless network  $\gamma_b$  with own base station and associated gateway entity is denoted  $P_{co}(\gamma_b); \gamma_b \in \gamma$ . The probability of deploying either MAVs or UAVs that spans the coverage of  $|\gamma|$  terrestrial wireless networks is denoted as  $P_{cy}(|\gamma|)$ . Given that the channel capacity of  $\gamma_b$  is denoted as  $Th(\gamma_b)$ ; the aggregate channel capacity associated with cloud content without and with the cyber-physical system is denoted as  $Th_1^{cl}(\gamma_b)$  and  $Th_2^{cl}(\gamma_b)$ , respectively.

$$Th_1^{cl}(\gamma_b) = \left( \prod_{b=1}^f P_{co}(\gamma_b) \times \sum_{b=f+1}^d P_{co}(\gamma_b) \right) \times Th(\gamma_b) \forall \gamma_b \quad (36)$$

$$Th_2^{cl}(\gamma_b) = \left( \left( \prod_{b=1}^f P_{co}(\gamma_b) \times \sum_{b=f+1}^d P_{co}(\gamma_b) \right) + \left( \prod_{b=1}^f P_{cy}(\gamma_b) \times \sum_{b=f+1}^d P_{cy}(\gamma_b) \right) \right) \times Th(\gamma_b) \forall \gamma_b \quad (37)$$

## 5. Simulation and discussion of results

This section presents and discusses the simulation results and performance benefits of the proposed mechanisms. It is divided into three parts. The first part presents the simulation parameters for the proposed mechanisms. The second part presents results indicating the performance of the space tourist subscriber. The third part presents results on the proposed cyber-physical aided cloud system.

### 5.1. Simulation parameters

The simulation parameters used to investigate the performance benefit of the handover mechanism for the space tourist subscriber are shown in **Table 3**. The parameters used to investigate the performance of the cyber – physical cloud access system are shown in **Table 4**.

### 5.2. Discussion of results – space tourist

The results of performance simulation are presented in this subsection. The performance benefit of the proposed handover mechanism is investigated using the channel capacity and latency as metrics. In addition, the performance benefit of incorporating aerial diversity is investigated using the aggregate channel capacity. The proposed aerial diversity mechanism is used to improve access to cloud content in terrestrial wireless networks.

S/N	Parameter	Value
1	Mean of transmit power $P_{tr}(\gamma_d, z')$ for the space vehicle.	202.9 mW
2	Mean of interference power for space vehicle in terrestrial plane, $P_{int}(\gamma_d, z')$	10.3 mW
3	Channel bandwidth in terrestrial plane, $B(z', b)$	1.5 MHz
4	Number of channels that are simultaneously accessed in terrestrial plane	4
5	Mean of transmit power of space vehicle in aerial plane, $P_{tr}(P_l, z')$	313 mW
6	Mean of interference power of space vehicle in aerial plane, $P_{int}(P_l, z')$	38.9 mW
7	Channel bandwidth in aerial plane	2.25 MHz
8	Number of channels that are simultaneously accessed in aerial plane	4
9	Mean of space vehicle transmit power $P_{tr}(p_c, z')$ in space plane.	227.6 mW
10	Average space vehicle interferer power in space plane, $P_{int}(P_c, z')$	32.6 mW
11	Channel bandwidth in space plane	5 MHz
12	Number of channels that are simultaneously accessed in space plane	4

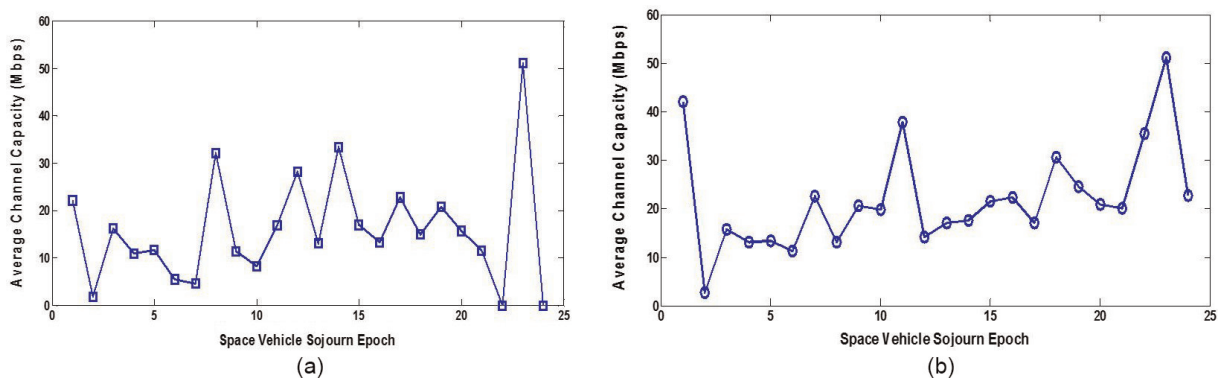
**Table 3.** Parameters used to investigate the performance of the handover mechanism.

Epoch 1				Epoch 2		
Base station index	Mean congestion probability	Mean MAV, UAV deployment probability	Mean backhaul throughput (Gbps)	Mean congestion probability	Mean MAV, UAV deployment probability	Mean backhaul throughput (Gbps)
1	0.3888	0.5685	35.3279	0.3664	0.4411	29.3312
2	0.7627	0.6175	29.5502	0.5061	0.4600	34.6044
3	0.5962	0.4267	19.5083	0.5352	0.5510	29.7344
4	0.7723	0.5495	21.4568	0.7274	0.5709	42.5083
5	0.6186	0.5712	22.3693	0.5334	0.5342	28.5267
6	0.6430	0.4176	35.3991	0.5230	0.6319	22.5061
7	0.3911	0.5927	30.0374	0.3145	0.6141	34.6840
8	0.3109	0.4928	31.4955	0.4969	0.5486	27.6927
9	0.4991	0.4411	21.9782	0.2291	0.4413	25.4814
10	0.5953	0.4336	49.2761	0.2747	0.4072	41.4290
11	0.4421	0.5791	28.4492	0.5575	0.6513	33.4003
12	0.6049	0.4986	41.8964	0.1730	0.5996	41.9393
13	0.3588	0.4654	13.7261	0.1503	0.2617	12.4052
14	0.5273	0.3811	28.5571	0.4534	0.3425	25.8474
15	0.5528	0.6437	45.3798	0.5048	0.5061	38.7138
16	0.6340	0.3282	11.0572	0.3233	0.5900	8.7650
17	0.3755	0.4869	25.0408	0.3963	0.5300	29.4266
18	0.5843	0.4820	34.9777	0.6028	0.4556	29.6869
19	0.3843	0.5792	30.5558	0.5304	0.5177	37.5723
20	0.5794	0.4632	29.2089	0.5655	0.5562	35.5610
21	0.6785	0.4600	31.2913	0.5464	0.5881	25.5595
22	0.2695	0.4369	37.4373	0.6859	0.6047	38.6078
23	0.5935	0.4550	40.7390	0.5582	0.4034	29.8772
24	0.3468	0.5875	35.4107	0.4412	0.4862	38.5071
25	0.4491	0.4572	39.0279	0.3655	0.4827	33.7495
26	0.4212	0.5881	27.4572	0.2794	0.5679	34.3914
27	0.4929	0.5598	30.8914	0.5723	0.5080	25.5206
28	0.5301	0.3996	34.4666	0.5208	0.6065	33.9866
29	0.5138	0.5482	21.8294	0.3015	0.5177	29.1524
30	0.4620	0.5018	42.4102	0.4737	0.4948	51.8990
31	0.5426	0.5050	18.7730	0.6504	0.3931	15.3598
32	0.6005	0.4215	35.4899	0.5052	0.5537	28.0000
33	0.1818	0.6061	38.9559	0.1964	0.5787	39.6352
34	0.5360	0.6202	10.5887	0.5137	0.6282	6.8601

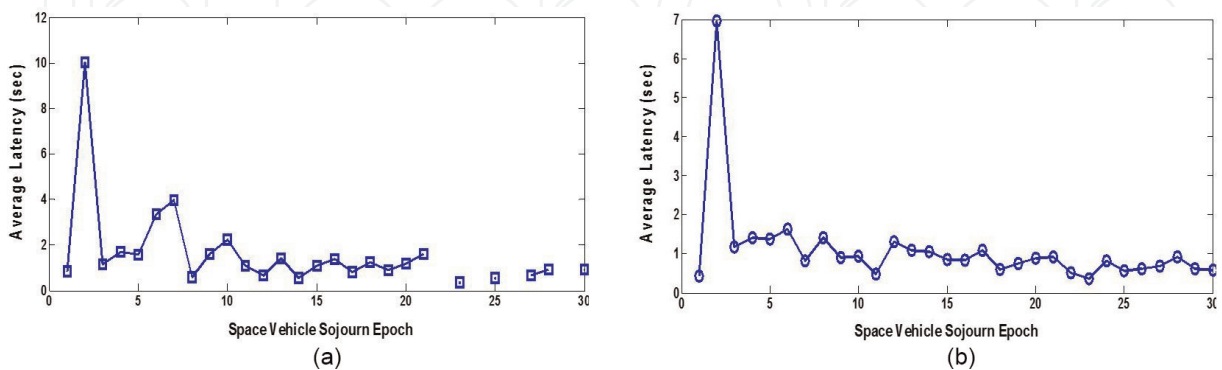
Epoch 1				Epoch 2		
Base station index	Mean congestion probability	Mean MAV, UAV deployment probability	Mean backhaul throughput (Gbps)	Mean congestion probability	Mean MAV, UAV deployment probability	Mean backhaul throughput (Gbps)
35	0.5848	0.4162	35.9282	0.4419	0.5076	29/9443
36	0.2103	0.5099	22.9408	0.4989	0.6247	38.3689
37	0.2227	0.6742	21.7225	0.5790	0.5600	44.0250
38	0.7069	0.6086	37.3177	0.6596	0.4421	27.1582
39	0.4296	0.6832	39.0351	0.4496	0.6709	34.6300
40	0.4539	0.4368	34.1860	0.4793	0.6442	36.4133

**Table 4.** Simulation parameters – cyber – physical aided cloud access mechanism.

Simulation result for the space vehicle average channel capacity is presented in **Figure 5**. **Figure 5** shows two sub-figures, i.e. a and b. The average channel capacity before and after the incorporation of the proposed handover mechanism is presented in **Figure 5a** and **b**,



**Figure 5.** Average channel capacity of the space vehicle before and after introducing the proposed scheme. (a) Average channel capacity achieved by space vehicle in Mbps in the absence of the proposed handover mechanism. (b) Average channel capacity achieved by space vehicle in Mbps after introducing the proposed handover mechanism.



**Figure 6.** Average latency of the space vehicle before and after introducing the proposed scheme. (a) Average latency achieved by space vehicle without the proposed handover mechanism. (b) Average latency achieved by space vehicle after the incorporation of the proposed handover mechanism.



respectively. Analysis of the result shows that the incorporation of the proposed mechanism enhances channel capacity. This is because of the continuity in data transmission during space vehicle sojourn. It is observed from the results that the channel capacity is enhanced on average by 18.4%.

The result for the latency of the space vehicle is presented in **Figure 6a** and **b**. **Figure 6a** and **b** shows the latency without and with the proposed mechanism, respectively. Results show that the proposed mechanism reduces the latency associated with accessing cloud content by the space vehicle. Analysis shows that the proposed handover mechanism reduces latency on average by 12%.

Aggregate channel capacity (bits per second)				
Epoch 1		Epoch 2		
Number of base stations	Without aerial diversity	With aerial diversity	Without aerial diversity	With aerial diversity
2	$6.76 \times 10^4$	$3.85 \times 10^4$	$1.88 \times 10^5$	$3.94 \times 10^5$
4	$1.61 \times 10^{11}$	$1.56 \times 10^{12}$	$8.78 \times 10^{12}$	$1.72 \times 10^{13}$
6	$1.73 \times 10^{19}$	$4.10 \times 10^{19}$	$1.73 \times 10^{20}$	$3.54 \times 10^{20}$
8	$3.33 \times 10^{26}$	$7.87 \times 10^{26}$	$1.89 \times 10^{27}$	$5.75 \times 10^{27}$
10	$4.45 \times 10^{33}$	$1.23 \times 10^{34}$	$1.10 \times 10^{34}$	$5.44 \times 10^{34}$
12	$1.01 \times 10^{41}$	$1.92 \times 10^{41}$	$2.05 \times 10^{41}$	$1.15 \times 10^{42}$
14	$5.74 \times 10^{47}$	$1.10 \times 10^{48}$	$3.82 \times 10^{47}$	$3.45 \times 10^{48}$
16	$6.40 \times 10^{54}$	$1.66 \times 10^{55}$	$7.47 \times 10^{54}$	$6.75 \times 10^{55}$
18	$9.49 \times 10^{61}$	$2.62 \times 10^{62}$	$8.71 \times 10^{61}$	$1.02 \times 10^{63}$
20	$1.18 \times 10^{69}$	$3.34 \times 10^{69}$	$1.74 \times 10^{69}$	$1.99 \times 10^{70}$
22	$1.16 \times 10^{76}$	$3.02 \times 10^{76}$	$2.42 \times 10^{76}$	$2.98 \times 10^{77}$
24	$1.94 \times 10^{83}$	$4.54 \times 10^{83}$	$4.04 \times 10^{83}$	$3.71 \times 10^{84}$
26	$3.17 \times 10^{90}$	$6.85 \times 10^{90}$	$8.46 \times 10^{90}$	$7.67 \times 10^{91}$
28	$9.40 \times 10^{89}$	$1.53 \times 10^{90}$	$1.26 \times 10^{90}$	$1.42 \times 10^{91}$
30	$9.40 \times 10^{89}$	$1.18 \times 10^{97}$	$1.26 \times 10^{90}$	$2.07 \times 10^{98}$
32	$7.64 \times 10^{96}$	$9.06 \times 10^{103}$	$1.11 \times 10^{97}$	$1.29 \times 10^{105}$
34	$5.85 \times 10^{103}$	$9.87 \times 10^{110}$	$1.11 \times 10^{104}$	$2.80 \times 10^{112}$
36	$5.74 \times 10^{110}$	$2.17 \times 10^{125}$	$8.62 \times 10^{110}$	$6.46 \times 10^{126}$
38	$1.31 \times 10^{125}$	$5.59 \times 10^{132}$	$1.74 \times 10^{125}$	$1.59 \times 10^{134}$
40	$3.69 \times 10^{132}$	$7.34 \times 10^{139}$	$4.43 \times 10^{132}$	$3.67 \times 10^{141}$
Mean improvement in aggregate channel capacity		70.3634%	Mean improvement in aggregate channel capacity	85.1583%

**Table 5.** Aggregate Channel capacity before and after incorporating aerial diversity.



The investigation also examines how aerial diversity enhances cloud content access. The use of aerial diversity ensures that network congestion does not affect the ability of the space vehicle subscriber to access cloud content. The metric used to investigate the performance benefit of incorporating aerial diversity is the aggregate channel capacity. This is the achieved channel capacity when the access of cloud content requires communications between multiple base stations. This is investigated using the parameters in **Table 4**. The aggregate channel throughput obtained via simulations for two epochs (i.e. epoch 1 and epoch 2) is shown in **Table 5**.

The simulation results in **Table 5** show that incorporating aerial diversity enhances the aggregate channel capacity. The incorporation of aerial diversity enables the delivery of cloud content when the terrestrial wireless network experiences congestion. The aggregate channel capacity is increased as aerial diversity influences data transmission for an increasing number of base stations. This is because the MAV and UAV are deployed in a manner that enables the delivery of cloud content for a larger terrestrial wireless network coverage area. Therefore, aerial diversity enhances the aggregate channel capacity associated with accessing cloud content by the space vehicle subscribers as seen in epochs 1 and 2. Aerial diversity enhances the aggregate channel capacity by 70.4 and 85.2% on average at epoch 1 and epoch 2, respectively.

## 6. Conclusion

This paper has proposed a distributed handover algorithm (DHA) for a network comprising terrestrial, aerial and space-based segments. DHA enables aerial platform to satellite handover and suborbital intersatellite handover in a space vehicle. The network uses ground stations deployed for radio astronomy. Simulation shows that DHA enhances channel capacity and reduces latency by 18.4 and 11.6% on average, respectively. The paper also proposed the joint use of manned and unmanned aerial vehicles for improving accessibility to cloud content while minimizing aviation safety concerns. The aerial vehicles are deployed when cloud access via terrestrial wireless networks is subject to significant latency due to network congestion. Simulations show that using aerial diversity reduces the effect of network congestion on terrestrial wireless networks. The aggregate throughput achieved on the terrestrial wireless network increases by up to 85% on average.

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