Article

Title

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Abstract

Hybrid satellite aerial terrestrial networks (HSATNs) are a promising solution towards tackling coverage and mobility issues in sixth generation (6G) networks.This paper presents a novel transmission scheme in the context of HSATNs,which allows pairs of terrestrial users to be simultaneously served via the satellite and the aerial base station (ABS).To this aim, non-orthogonal multiple access (NOMA) technique is adopted,at the ABS,by applying a rule-based hybrid NOMA and orthogonal multiple access (OMA) schemes.Comparisons between a standalone NOMA-based satellite transmission and the proposed method, reveal that significant sum-rate gains can be harvested under varying system parameters.

1. Introduction

The sixth generation (6G) network has already been commenced as a new research initiative, following on from the evolving 5G network.This new type of network envisions sophisticated device-to-device (D2D) and machine-to-machine (M2M) communications,innovative artificial intelligence (AI) techniques, Internet of Everything (IoE) applications connecting people, data, things through processes.Interoperability and convergence between terrestrial and satellite infrastructures will be a prerequisite in the 6G networking. Also, the new space era of non-terrestrial networks (NTNs) comprising of aerial networks, low Earth orbit (LEO) and especially very low Earth orbit (VLEO) satellites has emerged, enabling the path to 6G evolution.

Hybrid satellite-terrestrial networks (HSTNs) have been proposed as an efficient approach towards improving spectral efficiency and increasing the users' reliability all over the world.The available spectrum resources of these networks can be further exploited by adopting the non-orthogonal multiple access (NOMA) principle.However, in the absence of line-of-sight (LoS) conditions, the performance of satellite communication systems is severely deteriorating.

In the context of HSTNs, the unmanned aerial vehicle (UAV)-based communications are expected to improve the performance in various ways.In general, the UAV-aided NOMA schemes have gained the interest of the academia and the industry for various applications in the beyond 5G networks.Focusing on the scenario where the UAVs are adopted in satellite terrestrial communication networks, they could be employed in the NOMA scheme as an intermediate node for increasing the possibility of obtaining LoS conditions.

All-in-all, and to the best of our knowledge, no studies can be found related to the intelligent integration of aerial and satellite segments in 6G networks by utilizing a hybrid NOMA and orthogonal multiple access (OMA) transmission schemes. Motivated by this observation, in this paper, we propose a novel satellite aerial terrestrial cooperative network scheme, which will be termed SATCON. More specifically, SATCON is formed with the integration of aerial base station (ABS) in the existing satellite network by efficiently combining two unsupervised machine learning (ML) algorithms, namely k-means and k-medoids. Furthermore, the proposed system promotes efficient cooperation between ABS and satellite through an innovative hybrid NOMA/OMA approach, avoiding the waste of resources and energy.Compared to standalone satellite NOMA transmission with optimal user pairing, namely SAT-NOMA, SATCON increases the sum rate and, at the same time, provides higher spectral efficiency for varying satellite channel conditions and ABS bandwidth.

2. Materials and Methods

As shown in Figure 1, the considered SAGIN consists of **U** UAVs denoted by $\mathcal{U} = 1, 2, \ldots, U$ and **S** LEO satellites indicated by $\mathcal{S} = 1, 2, \ldots, S$. In addition, **K** IoT devices randomly scattered on the ground are represented as $\mathcal{K} = 1, 2, \ldots, K$.

In the downlink, UEs may receive data either directly from the LEO satellite or through a UAV-assisted relaying link over the air-to-ground (A2G) channel. Satellite-side user pairing is first established based on direct downlink transmission, which serves as the reference for subsequent transmission decisions.Under this pairing, UAV-assisted transmission is activated only when it can provide a strict rate improvement over direct satellite delivery. Specifically, if both paired users achieve higher downlink rates via the UAV, UAV-assisted NOMA transmission is employed. If only one user benefits from UAV relaying, UAV-assisted OMA transmission is selectively applied to that user in order to avoid any performance degradation of the other. Otherwise, when UAV-assisted transmission cannot outperform direct satellite transmission for either user, both users are served directly by the satellite.
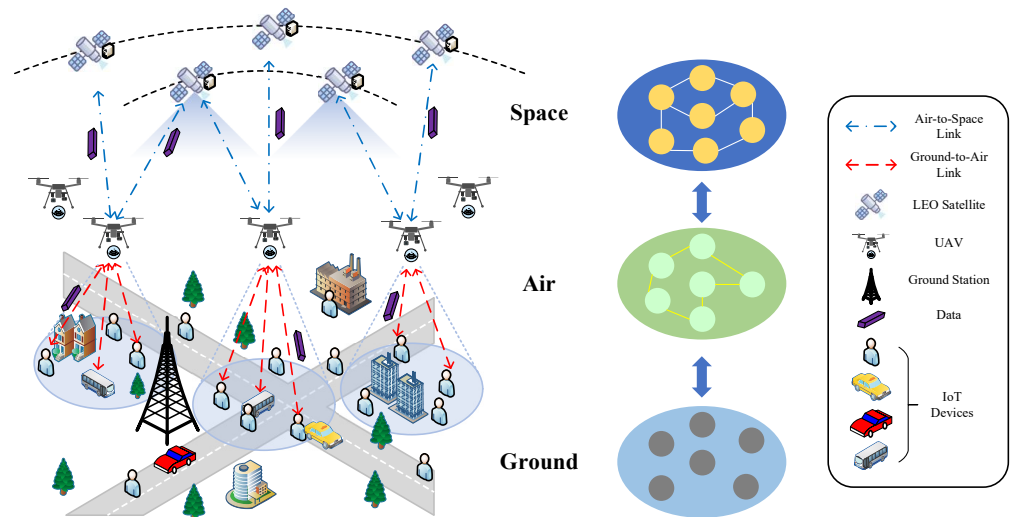

Figure 1. Illustration of the uplink communication procedure in SAGIN, where UAVs act as aerial aggregators to collect data from spatially distributed IoT devices and subsequently offload the aggregated data to LEO satellites.

To characterize the downlink transmission options described above, the satellite downlink is modeled using a land mobile satellite(LMS) channel. The overall channel coefficient between LEO satellite s and UE i is expressed as

$$h_i^s = \sqrt{L_i^s} \cdot g_i^s,\tag{1}$$

where L_i^s represents the large-scale free-space path loss given by

$$L_i^s = \left(\frac{c}{4\pi f_c d_i^s}\right)^2,\tag{2}$$

with f_c denoting the carrier frequency, d_i^s the satellite-to-UE distance, and c the speed of light.

The small-scale fading coefficient g_i^s follows the Loo model,characterizing the composite fading as a superposition of a dominant line-of-sight (LoS) component and multipath fading

$$g_i^s(t) = A_i(t)e^{j\phi_i(t)} + m_i(t),\tag{3}$$

where $A_i(t)$ represents the LoS amplitude with $20\log_{10} A_i(t) \sim \mathcal{N}(\mu, \sigma^2)$, and $m_i(t) = m_{I,i}(t) + jm_{Q,i}(t)$ denotes the multipath component with $m_{I,i}, m_{Q,i} \sim \mathcal{N}(0, \sigma_m^2)$.The parameters are set as $\mu = -1$ dB, $\sigma = 2$ dB, corresponding to a suburban environment.

Furthermore, the Doppler effect induced by satellite motion is captured using the classical Jakes spectrum with maximum Doppler shift $f_D = vf_c/c$, where v denotes the relative velocity between the satellite and UE.

For UAV-assisted transmission, data are forwarded to UEs through an air-to-ground (A2G) link. The channel coefficient between the UAV and UE i is denoted by h_i^d and can be expressed as

$$h_i^d = \sqrt{L_i^{\text{A2G}}} \cdot g_i^d,\tag{4}$$

where L_i^{A2G} represents the large-scale path loss and g_i^d denotes the small-scale fading.

Following the elevation-angle-dependent model by Al-Hourani *et al.* [8], the path loss accounts for probabilistic LoS and NLoS propagation in urban environments. The LoS probability is given by

$$P_{\text{LoS}}(\theta_i) = \frac{1}{1 + a\exp(-b[\theta_i - a])},\tag{5}$$

where $\theta_i = \arcsin(H/\sqrt{H^2 + d_i^2})$ is the elevation angle, H is the UAV altitude, d_i is the horizontal distance, and (a, b) are environment-dependent parameters. For urban environments, we adopt $a = 9.61$ and $b = 0.16$ [8].

The composite path loss is then computed as

$$L_i^{\text{A2G}} = P_{\text{LoS}}(\theta_i) \cdot L_i^{\text{LoS}} + [1 - P_{\text{LoS}}(\theta_i)] \cdot L_i^{\text{NLoS}},\tag{6}$$

where

$$L_i^{\text{LoS}}(\text{dB}) = 20\log_{10}\left(\frac{4\pi f_c d_i^{\text{3D}}}{c}\right) + \eta_{\text{LoS}},\tag{7}$$

$$L_i^{\text{NLoS}}(\text{dB}) = 20\log_{10}\left(\frac{4\pi f_c d_i^{\text{3D}}}{c}\right) + \eta_{\text{NLoS}},\tag{8}$$

with $d_i^{\text{3D}} = \sqrt{H^2 + d_i^2}$ denoting the 3D distance, and $\eta_{\text{LoS}} = 1$ dB, $\eta_{\text{NLoS}} = 20$ dB representing the excessive path loss for LoS and NLoS links, respectively [8].

It should be emphasized that the downlink rate delivered to a UE via UAV-assisted relaying is jointly determined by the A2G access link and the satellite-to-UAV (S2A) backhaul. Since the UAV can only forward the data it receives from the satellite, the capacity of the S2A backhaul may limit the effective downlink rate, preventing UAV-assisted transmission from consistently outperforming direct satellite delivery.

All downlink links are assumed to be impaired by additive white Gaussian noise (AWGN). These channel characteristics explain why UAV-assisted relaying may provide significant rate gains for some users while offering no advantage for others, thereby motivating rate-based downlink transmission mode selection.

3. SATCON

3.1. ABS placement process

For the intelligent integration of the ABS into the existing satellite network, the combination of the k-means and kmedoids unsupervised ML methods is utilized. The two algorithms aim to find the point $p \in W$ where $p = (x_1^p, y_1^p, z_1^p)$ so that the sum of the distances of the users from this point is minimized. The total within-cluster dissimilarity of the kmeans c and k-medoids m algorithms is $A_q = \sum_{u_i \in U} \|u_i - p_q\|^2$, where $q = \{c, m\}$. The objective of these two methods is to determine the point p_q that minimizes A_q and it can be expressed as follows

$$\arg \min_{p_q \in W} \sum_{u_i \in U} \|u_i - p_q\|^2. \tag{9}$$

From the two suggested points, p_c and p_m, given from kmeans and k-medoids, respectively,if $A_c < A_m$ then $p = p_c$, otherwise $p = p_m$.Due to the nature of these two ML methods to create groups through the input data, i.e., the coordinates of the users U, the initial height of the ABS will be the same as the average height of the users. Therefore, to obtain the optimal altitude at which ABS provides the best quality of service (QoS) to the MTs, first, we should identify the farther MT_i from the point p, where ABS is placed. Thereinafter, we should determine the height of the ABS h where pathloss with the MT_i is minimized through solving $\frac{\partial L_i^{A2G}(h, r_i)}{\partial h} = 0$.

3.2. Satellite NOMA transmission

For the satellite transmission, each MT_l ($1 \le l \le N$) periodically reports the channel state information (CSI) of the LMS channel to the satellite that receives the complex channel coefficient h_l^s and calculates the channel gain including additional gains, losses, and the noise power of the satellite receiver N_s as

$$\Gamma_l^s = \frac{G_t^s G_r^s}{L_l^{FS} N_s} |h_l^s|^2. \tag{10}$$

The satellite aims to create K pairs of MTs, where each pair will share the same sub-channel in the power and time domain, assigning different power allocation factors of the total satellite power P_s to each MT belonging to a pair. Towards this end, a NOMA optimal user pairing policy is adopted, where the satellite sorts the MTs in ascending order by the channel gain $\Gamma_1^s \le \Gamma_2^s \le \cdots \le \Gamma_{2K}^s$ and matches the user MT_k with the user MT_{2K-k+1}, for $1 \le k \le K$.Hence, each pair consists of the strong satellite channel user MT_j^s, and the weak satellite channel user MT_i^s, with channel gains $\Gamma_j^s \ge \Gamma^s$,respectively.

The optimal power allocation factor β_j^s can be calculated by the following expression

$$\beta_j^s = \frac{\sqrt{1 + \Gamma_i^s P_s} - 1}{\Gamma_i^s P_s}. \tag{11}$$

According to the principle of NOMA, MT_i^s will immediately decode its own signal by the received satellite signal, while MT_j^s should first estimate the signal of the MT_i^s and then perform successive interference cancellation (SIC) to retrieve its own signal. The achievable rates of MT_j^s and MT_i^s are

$$R_j^s = \frac{B_s}{K} \log_2\left(1 + \beta_j^s P_s \Gamma_j^s\right), \tag{12}$$

$$R_i^s = \frac{B_s}{K} \log_2\left(1 + \frac{(1 - \beta_j^s) P_s \Gamma_i^s}{\beta_j^s P_s \Gamma_i^s + 1}\right). \tag{13}$$

3.3. ABS hybrid NOMA/OMA transmission

As described previously, ABS is integrated into the satellite network to improve the QoS of terrestrial users. Towards this end, the ABS should first receive and decode the NOMA superimposed signals of each pair of MTs via the S2A channel. The S2A channel gain can be expressed as

$$\Lambda_{sd} = \frac{G_t^s G_r^{sd}}{L_{sd}^{FS} N_{sd}}. \tag{14}$$

The maximum achievable decoding rates which succeed by the ABS through the S2A channel for each MT_j^s and MT_i^s in pair are

$$R_j^{sd} = \frac{B_s}{K} \log_2\left(1 + \beta_j^s P_s \Lambda_{sd}\right), \tag{15}$$

$$R_i^{sd} = \frac{B_s}{K} \log_2\left(1 + \frac{(1 - \beta_j^s) P_s \Lambda_{sd}}{\beta_j^s P_s \Lambda_{sd} + 1}\right). \tag{16}$$

Note that, the ABS obtains all the pair indices from the VLEO through a dedicated control channel to identify the users comprising each pair and their role, e.g., strong or weak satellite channel users. Also, the ABS acquires the achievable rate R_l^s of each MT_l with the satellite, through the same channel.

Next, the ABS should forward the decoded signals to the MTs through the A2G channel, utilizing the proposed hybrid NOMA/OMA transmission scheme. Consequently, we consider that each MT_l reports the CSI of the corresponding A2G link to the ABS. Therefore, the ABS calculates the channel gain of the A2G link for each M Tl as follows

$$\Gamma_l^d = \frac{G_t^d G_r^d}{L_l^{A2G}(h, r_l) N_d} |h_l^d|^2. \tag{17}$$

Following the same NOMA user pairing policy as the VLEO, the ABS forms K MT pairs, considering now the channel gains of the A2G links. Therefore, each pair consists of the strong A2G channel user MT_j^d, and the weak A2G channel user MT_i^d, where $\Gamma_j^d \geq \Gamma_i^d$. Subsequently, calculates the optimal power allocation factor β_j^d for the MT_j^d by replacing s with d in expression 11. Also, the achievable rates in NOMA, R_j^d and MT_i^d, are given by the expressions 12 and 13, respectively, by replacing again s with d. The rates that ABS can offer to MT_j^d and MT_i^d, utilizing the NOMA technique, are $R_j^{dn} = \min\left(R_j^d, R_j^{sd}\right)$ and $R_i^{dn} = \min\left(R_i^d, R_i^{sd}\right)$, respectively.

Lastly, the ABS has to decide whether it is profitable for each pair of MTs to transmit the superimposed signal or to transmit only the signal of one MT of each pair utilizing the OMA technique. Also, the ABS can avoid forwarding the satellite signals if the ABS

transmission is not profitable for both MTs in pair. Therefore, the achievable rate that each MT_l can achieve from the ABS through OMA, is equal to

$$R_l^o = \frac{B_d}{K} \log_2 \Big(1 + P_d \Gamma_l^d \Big). \tag{18}$$

Each MT_l will experience higher rates if the ABS uses OMA, i.e., $R_l^o \geq R_l^d$, since the same bandwidth as NOMA is allocated for OMA transmission, and whole P_d is allocated to MT_l. However, the maximum achievable OMA rate of MT_l is restricted by the expression $R_l^{do} = \min\Big(R_l^o, R_l^{sd} \Big)$,since the ABS may provide a higher rate to the MT_l,but the rate at which ABS decoded its signal from the VLEO is lower and vice versa. There are four different cases that the ABS considers for each MT pair

- **if** $R_i^s < R_i^{dn}$ **and** $R_j^s < R_j^{dn}$: In this case, the pair of MTs formed by the ABS profits from the NOMA transmission as both MTs achieve greater rates if served from the ABS instead of the satellite.
- **if** $R_i^s < R_i^{dn}$ **and** $R_j^s \geq R_j^{dn}$: In this case, only MT_i^d profits from the ABS transmission. Thus, the ABS utilizes OMA and transmits only to MT_i^d or the timeslot allocated to this pair. MT_i^d achieves a rate equal to R_i^{do}.
- **if** $R_i^s \geq R_i^{dn}$ **and** $R_j^s < R_j^{dn}$: In this case, only MT_j^d profits from the ABS transmission. Therefore, the ABS utilizes OMA and transmits only to MT_j^d for the timeslot allocated to this pair. MT_j^d achieves a rate equal to R_i^{do}.
- Otherwise, the communication for this MT pair is not profitable and ABS does not transmit to these pair of users in order to save resources.

4. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

4.1. Subsection

4.1.1. Subsubsection

Bulleted lists look like this:

- First bullet;
- Second bullet;
- Third bullet.

Numbered lists can be added as follows:

1. First item;
2. Second item;
3. Third item.

The text continues here.

4.2. Figures, Tables and Schemes

All figures and tables should be cited in the main text as Figure 2, Table 1, etc.

Figure 2. This is a figure. Schemes follow the same formatting.

Table 1. This is a table caption. Tables should be placed in the main text near to the first time they are cited.

Title 1	Title 2	Title 3
Entry 1	Data	Data
Entry 2	Data	Data [1]

[1] Tables may have a footer.

The text continues here (Figure 3 and Table 2).
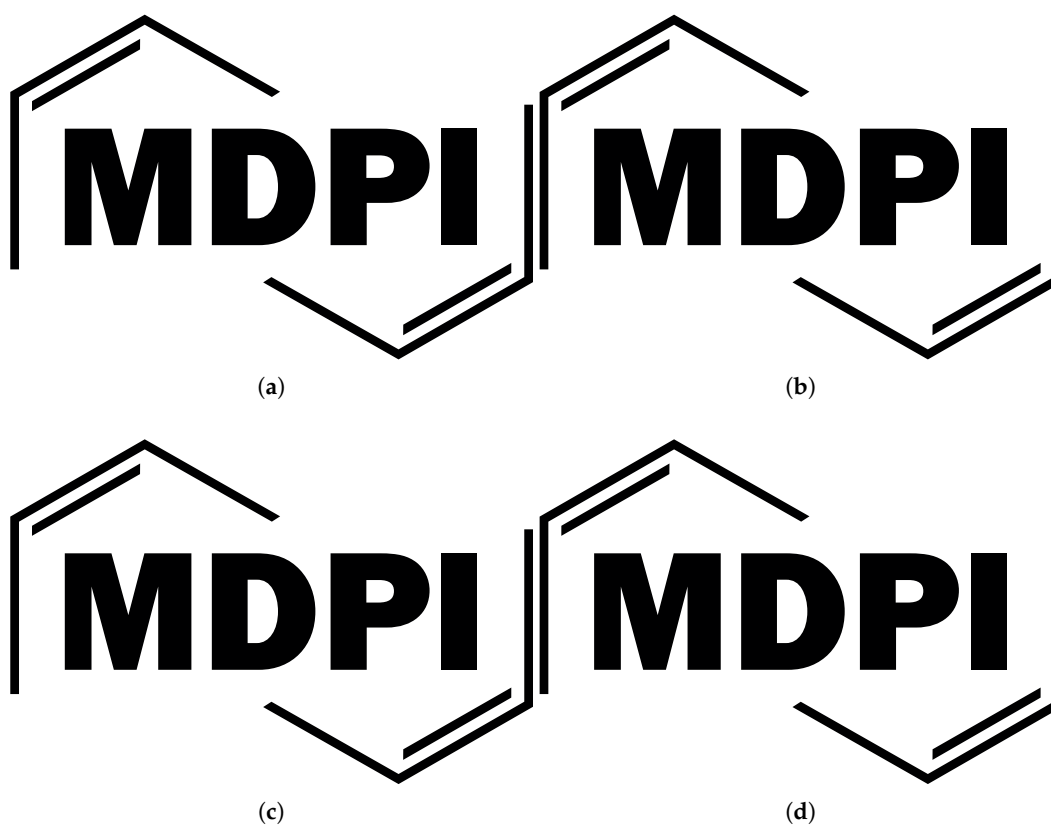
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(**a**)

(**b**)

(**c**)

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Figure 3. This is a wide figure. Schemes follow the same formatting. If there are multiple panels, they should be listed as: (**a**) Description of what is contained in the first panel. (**b**) Description of what is contained in the second panel. (**c**) Description of what is contained in the third panel. (**d**) Description of what is contained in the fourth panel. Figures should be placed in the main text near to the first time they are cited. A caption on a single line should be centered.

Table 2. This is a wide table.

Title 1	Title 2	Title 3	Title 4
	Data	Data	Data
Entry 1 *	Data	Data	Data
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Entry 2	Data	Data	Data
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* Tables may have a footer.

Text.

Text.

4.3. Formatting of Mathematical Components

This is the example 1 of equation:

$$a = 1, \tag{19}$$

the text following an equation need not be a new paragraph. Please punctuate equations as regular text.

This is the example 2 of equation:

$$a = b + c + d + e + f + g + h + i + j + k + l + m + n + o + p + q + r + s + t + u + v + w + x + y + z \tag{20}$$

Please punctuate equations as regular text. Theorem-type environments (including propositions, lemmas, corollaries etc.) can be formatted as follows:

Theorem 1. *Example text of a theorem.*

The text continues here. Proofs must be formatted as follows:

Proof of Theorem 1. Text of the proof. Note that the phrase "of Theorem 1" is optional if it is clear which theorem is being referred to. □

The text continues here.

5. Discussion

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

6. Conclusions

This section is not mandatory, but can be added to the manuscript if the discussion is unusually long or complex.

7. Patents

This section is not mandatory, but may be added if there are patents resulting from the work reported in this manuscript.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualiza-

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Funding: Please add: "This research received no external funding" or "This research was funded by NAME OF FUNDER grant number XXX." and and "The APC was funded by XXX". Check carefully that the details given are accurate and use the standard spelling of funding agency names at https://search.crossref.org/funding, any errors may affect your future funding.

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Written informed consent for publication must be obtained from participating patients who can be identified (including by the patients themselves). Please state "Written informed consent has been obtained from the patient(s) to publish this paper" if applicable.

Data Availability Statement: We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section "MDPI Research Data Policies" at https://www.mdpi.com/ethics.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronym
LD	Linear dichroism

Appendix A

Appendix A.1

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data are shown in the main text can be added here if brief, or as Supplementary Data. Mathematical proofs of results not central to the paper can be added as an appendix.

Table A1. This is a table caption.

Title 1	Title 2	Title 3
Entry 1	Data	Data
Entry 2	Data	Data

Appendix B

All appendix sections must be cited in the main text. In the appendices, Figures, Tables, etc. should be labeled, starting with "A"—e.g., Figure A1, Figure A2, etc.

References

1. Author 1, T. The title of the cited article. *Journal Abbreviation* **2008**, *10*, 142–149.
2. Author 2, L. The title of the cited contribution. In *The Book Title*; Editor 1, F., Editor 2, A., Eds.; Publishing House: City, Country, 2007; pp. 32–58.
3. Author 1, A.; Author 2, B. *Book Title*, 3rd ed.; Publisher: Publisher Location, Country, 2008; pp. 154–196.
4. Author 1, A.B.; Author 2, C. Title of Unpublished Work. *Abbreviated Journal Name* year, *phrase indicating stage of publication (submitted; accepted; in press)*.
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7. Author 1, A.B. Title of Thesis. Level of Thesis, Degree-Granting University, Location of University, Date of Completion.
8. Al-Hourani, A.; Kandeepan, S.; Lardner, S.Optimal LAP Altitude for Maximum Coverage.*IEEE Wireless Commun. Lett.* **2014**, *3*, 569–572.