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Towards 6G Energy Sustainability: Effect of a Reduced UAV Power Control Factor on Downlink Transmission

Chigozirim Ajaegbu[1] , Emmanuel Ogiemwonyi Arakpogun [2] , Samuel O. Hassan[3]

[1]Computer Science Department, Babcock University, Ilishan-Remo, Ogun State Nigeria
[2]Newcastle Business School, Northumbria University, Newcastle upon Tyne, United Kingdom
[3]Department of Mathematical Sciences, Olabisi Onabanjo University, Ago-Iwoye, Nigeria

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Abstract

Unmanned Aerial Vehicles (UAVs) have emerged as crucial components of 5G Internet of Things (IoT) networks, expanding coverage and capacity in various applications. While prior research has extensively examined the impact of power control factor adjustments on UAV uplink transmission, limited attention has been devoted to UAV downlink transmission, which is vital for seamless connectivity and quality of service. In this study, we address this research gap by investigating the effects of reduced power control factors on UAV downlink transmission. We use MATLAB simulations to model how user equipment (UE) is randomly placed in a UAV network. We then check the coverage probability and spectral efficiency for UAV altitudes between 200 and 500 m, taking into account different power control factors in the downlink transmission. Our findings show that a certain threshold of 0.05 for the power control factor keeps coverage probabilities at different heights, making sure that served UEs have enough signal strength. Surprisingly, there is no significant change in spectral efficiency when compared to the baseline results. This means that lowering the power control factor does not hurt spectral efficiency in UAV downlink transmission. These results help us figure out how to make UAV communication work better in 5G IoT networks. They also help us make smart choices about how to change the power to make up for lost downlink signals while keeping the quality of service high. Moreover, our study lays the groundwork for future research in UAV deployment and communication optimization within advanced wireless networks.

Keywords: 6G technology, Unmanned Aerial Network, Heterogenous Network, power control factor, Energy Efficiency

1. Introduction

The introduction of 5G technology heightened research interest in the field of cellular technology. Its robust spectrum of resources contributed greatly to more technological innovations, with one of them being the evolution of the Internet of Things (IoT) [1]. 5G, beyond giving rise to IoT technology, also enabled network integration studies in different directions, such as the integration of satellite communication and 5G, the integration of unmanned aerial vehicle (UAV) networks and 5G, and the integration of space-air-ground networks [2].

Besides these benefits of the 5G advent, it has also presented some challenges to its deployment and use, with one of them being the high rate of power consumption among equipment and devices within the network, hence demanding provision for sustainable energy

*Email: ajaegbuc@babcock.edu.ng

solutions [3]. However, it has been demonstrated that it won't be possible to completely execute all 5G needs until 2030, thus shifting the focus of development to 6G technology. Studies have shown that 6G technology will not be about moving data around but will include communication and integration services [4]. The expected integration services of 6G with the goal of achieving seamless global coverage are not significantly different from those of 5G implementation; the only difference is that both are expected to work concurrently in a 6G network. However, it was discovered that of all the anticipated challenges listed in (4), less attention was paid to the issue of power consumption in the 6G network, which, without a doubt, will be of greater interest to researchers as the network strives for seamless communication among devices at the same time.

In [5], the authors argued that energy consumption will remain one of the major concerns in the cellular network, and in order to boost 6G energy efficiency, models that can handle its complexities are needed. Also, it has been established that the battery life of devices is solely dependent on the transmission and reception duty cycles, meaning that the power consumption rate could only be reduced if devices transmitted or received data for only a few minutes per cycle [6]. However, a reduction in transmission and reception duty cycles seems impractical with cellular generation technologies, hence the major focus on managing the battery life of equipment or devices contributing to seamless network integration in a 6G network. Hence, the motivation of this study is in the direction of UAV power control.

The massive support of 5G for the IoT has given rise to research attention when integrated with a UAV. One of the reasons was that the airborne energy of UAVs is very limited, necessitating the use of a sustainable energy efficiency model in such an integration setting. UAV power control has been heavily studied around 5G technology, considering its effect on cellular indicators like coverage probability, spectral efficiency, and energy efficiency. Although the majority of the study focused more on the uplink transmission, with output showing good effects of optimal UAV energy management, it is also very important to redirect focus to the expected 6G technology, but this time in the downlink transmission. This is needed because UAVs, used as base stations for UEs, have a vital role to play in keeping all UEs connected to them in service; hence, the need to maintain sustainable UAV energy while limiting path loss effects in the downlink channels. Thus, the study complements [2] by examining the effect of a reduced power control factor on the downlink transmission of UAVs.

The rest of this paper is organized as follows: Section 2 introduces the literature review along with related works. Section 3 describes the system model for communications between UAVs and UEs. In Section 4, the coverage probability and spectral efficiency of the downlink transmission are shown as a function of the power control factor and the height of the UAV. In Section 5, we provided the conclusion and recommendation for further studies.

2. Literature Review

UAVs (unmanned aerial vehicles) have shown promise for the wireless network's future. It has been considered a viable solution for the extension of network coverage (see Figure 1) to areas where the terrestrial network has been overloaded or to blind spots [6].

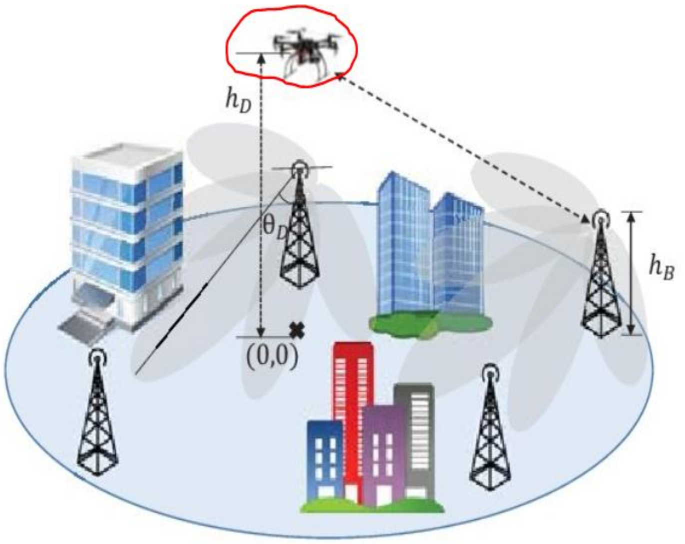


Figure 1: Scenario of a UAV connected to cells [6]

UAV operations in the extension of coverage to an overloaded area have been demonstrated and realized effectively in [7, 8]. Its deployment within the terrestrial ecosystem has been impactful, and it is expected to become predominant in the next decade [9], with the help of features such as flexibility, ease of deployment, a direct communication link with ground users, and automation [10]. UAVs offer the flexibility of operating with a joint radio resource with the terrestrial base station in a well-coordinated manner [11]. In the current 5G ecosystem, UAVs have been seen as the bedrock for achieving maritime communication networks, as the deployment of communication infrastructure in the ocean is very challenging [12]. Along with satellites in an integrated network (see Figure 2), it not only increases coverage but also makes it possible for multiple devices to share data, even if they use different communication protocols [13].

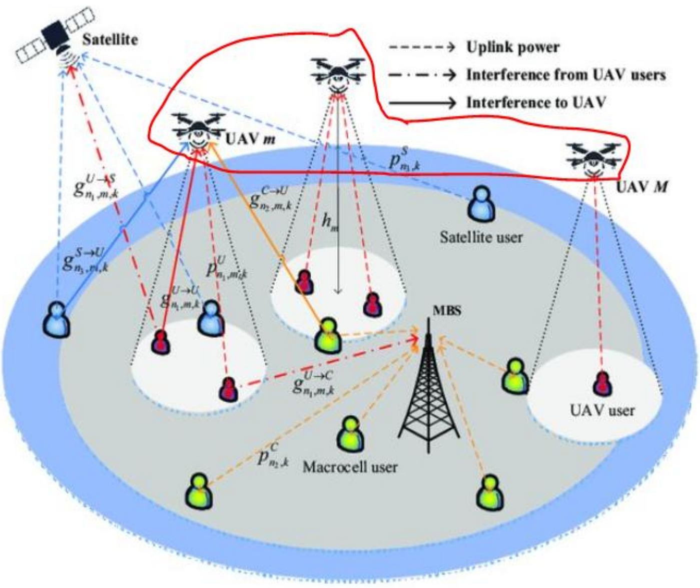


Figure 2: The structure of a satellite, UAV, and macrocell three-tier hybrid network [12]

UAVs and satellites have been proposed as solutions to enable the huge set of IoT solutions yet to be properly integrated with 5G frameworks [14]. Some researchers perceive the space-air-ground architecture as going beyond the normal IoT to what is seen as the Internet of Remote Things (IoRT), as presented in Figure 3 [14, 15].

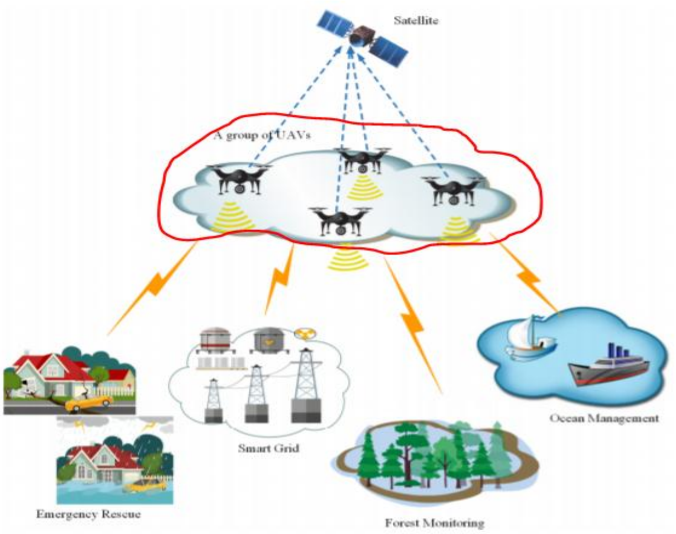


Figure 3: Internet of Remote Things Scenario [15]

There were some good things about this integration scenario, but there were also problems that were thought to be unique to hybrid-tier heterogeneous network integration. These included problems with deployment, planning, mobility control, operational altitude, terrestrial drones, energy consumption, limited endurance, lack of regulation, and providing backhaul connections to cellular networks [16]. Cross-tier interference has been seen as one of the problems that could happen in this kind of network situation. This means that power control management in the direction of the UAV network in a heterogeneous network needs more attention [17]. So, it's very important to look into how the power control factor changes the coverage probability and spectral efficiency of a UAV network when it's part of a larger network.

2.1 Related Works

In [2], a binary exponential power control algorithm was proposed for a 5G-UAV integrated network. Their study focused on uplink transmission and analyzed the effects of the power control factor on key cellular parameters such as coverage probability, spectral efficiency, and energy efficiency. Similarly, [26] conducted an uplink analysis of UAV communication with power control, considering a single UAV user's equipment, and identified an optimal power control factor for maximizing communication energy efficiency.

In the context of UAV-assisted V2X networks, [19] suggested a way to offload computing tasks that used less energy and combined data from multiple sensors. Their approach optimized bandwidth and computational resources while making informed offloading decisions within the UAV-aided system. On a related note, [20] studied downlink transmission in a 5G heterogeneous network involving a UAV, a small base station, and a ground-based dual-mode mmWave antenna. They developed a two-layer optimization framework to determine an efficient coverage radius for the UAV and implement energy-efficient radio resource management for the entire network.

Looking ahead to 6G networks, [21] proposed a UAV energy-efficient framework that utilized distributed federated learning. This approach enabled local clients to update their machine-learning models without requiring direct connectivity to the corresponding UAV. Similarly, [22] investigated UAV energy efficiency in the context of federated learning but adopted a deep reinforcement learning optimization approach. Their method involved adjusting the CPU frequency of devices and uploading wireless bandwidth for each device to achieve improved energy efficiency.

In this study, we want to find out what happens when the power control factor is lowered and how that affects the coverage probability and spectral efficiency of communication between UAVs and UEs. While prior research has extensively explored various aspects of UAV integration with 5G and 6G networks, there remains a critical need to assess the downlink transmission scenario and its implications for UAV power control. By employing advanced modeling techniques and simulations in MATLAB, we aim to provide valuable insights into optimizing UAV communication in advanced wireless networks, particularly in the context of 6G integration. Our analysis will shed light on how a reduced power control factor affects network performance, ensuring sustainable UAV energy management while maintaining efficient downlink communication with UEs.

3. System model

The scenario studied in this article is such that a UAV is acting as a base station for areas that could not be covered by the ground station. Figure 4 shows the signal departure from the UAV to the UE. This is because UEs do experience path loss in the downlink channel, which could be due to obstacles like tall buildings, trees, and other things happening while the UAV hovers around in a circle or stays in one place. To show where the UE and the UAV are in relation to each other, the height of the UAV is assumed to change. This explains the variation in UAV altitudes shown by the five different altitudes.

3.1 Wireless System Model

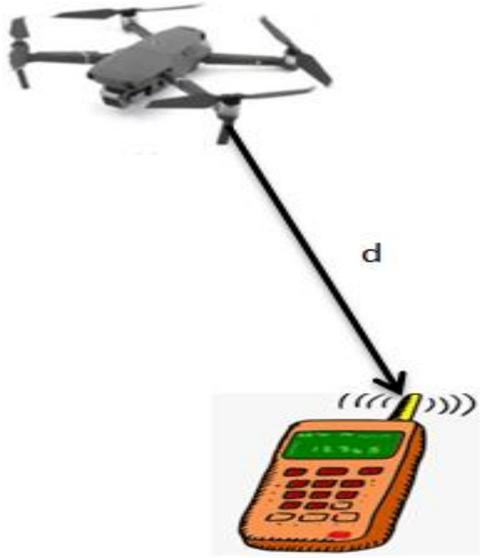
The wireless system paradigm for the discussed downlink UAV-to-UE communications is introduced in this subsection.

The path loss model is defined as $\varsigma = Ad^{\alpha}$, where d is the distance between the UAV and UE, α is the path loss exponent, and A is a constant coefficient related to topographic features.

The study adopted an open-loop power control technique [23], taking into account the impact of path loss on the transmission power of UAVs. When the route loss is greater, more transmission power is needed. Additionally, it is believed that the UAV transmission power is limited to a maximum amount. Consequently, the model for the UAV transmission power is

$$P^{U} = min\,(P_0 \zeta^{\epsilon}, P_{max}) \tag{1}$$

where P_0 is the UAV-specific reference transmit power, which is smaller when compared to the ground UEs due to the presence of UAV LOS propagation; ϵ is the power control factor; and ζ^{ϵ} reflects the transmission power compensation out of the path loss from the UAV UE to its serving BS; P_{max} is the UAV-specific maximal transmit power.



The UAV uplink signal-to-noise ratio (SNR) is

$$SNR = \frac{P^{U}\zeta^{-1}g}{N} \quad (2)$$

Where the path loss gain is given by ζ^{-1}, which is inversely proportional to the path loss; N is the additive white Gaussian noise (AWGN) power at the UAV; and g is the fading, assumed to be Rayleigh fading, thus g ∼ exponent (1);.

3.2 Performance Metrics

There have been few studies on the effects of power control factors on UAV energy efficiency in downlink transmission involving UAV-UE communication. One study [24, 25] looked at a joint UAV channel modeling and power control model. This model gave a power control model that was used to look into things like the UAV system's coverage probability, spectral efficiency, and energy efficiency in a heterogeneous network. In their study, they adopted the binary exponential increase algorithm with a power control factor of 0.1. This enabled the UAV's power to increase slowly when trying to access the channel from the BS. The power control factor of the UAV transmitter was given as [2]:

$$\epsilon = 2^{(i-1)} \times \epsilon\_step \quad (3)$$

where ϵ is the power control factor and ϵ_step is the power control factor step size. Equation 3, as proposed around 5G, focused on the uplink transmission channel and ignored the need for downlink channel performance when the UAV acts as a BS to UEs. Thus, there is a need for a reduced power control factor for better energy conservation in the downlink transmission, as shown in (4).

$$\epsilon = (1/2^{(i-1)}) \times \epsilon\_step \quad (4)$$

The above equation was used to further study the coverage probability and spectral efficiency. The coverage probability is defined as:

$$P_c(\gamma) = P_r[SNR > \gamma] \quad (5)$$

where γ is the SNR threshold. In line with [11], the spectral efficiency (SE) can be computed as

$$SE(\gamma_0) = \int_{\gamma_0}^{+\infty} log_2(1+\gamma) f_{SNR}(\gamma) d\gamma \quad (6)$$

where γ_0 is the minimal working SNR, and $f_{SNR}(\gamma)$ is the probability density function (PDF) of SNR. Considering that $P_c(\gamma)$ is the complementary cumulative distribution function (CCDF) of SNR, $f_{SNR}(\gamma)$ can be derived as

$$f_{SNR}(\gamma) = \frac{\partial(1 - P_c(\gamma))}{\partial_\gamma} \quad (7)$$

4. RESULTS AND DISCUSSION

The adopted parameters, as presented in Table 1, were used to measure and obtain results for the coverage probability and spectral efficiency.

Table 1: Parameters and Description

Parameters	Description
Leader UAV altitude	200-500m
Path-loss exponent(α)	2.09
P_{max}	44.43dBm
AWGN power of the BS	-99dBm
Propagation coefficient	$10^{10.38}$
Power Control step size	0.1
UAV specific reference transmit power	-16dBm

4.1 Coverage Probability

The coverage probability is computed using (8), as presented in [26].

$$P_c(\gamma) = \exp(-\frac{N\gamma\varsigma}{P_0\varsigma^{\epsilon-1}}) \quad (8)$$

where (8) is obtained by including (2) in (5). Hence**,** the proposed power control factor adjusts the downlink transmission power of the UAV in order to compensate for the different path losses while establishing a connection with the user's equipment. The modified power factor in (4) was used to study the coverage probability as presented in (8) and plotted against the power control factor with different altitudes d in the order of 200 m, 300 m, 400 m, and 500 m, as shown in Figures 4–7.

- For the different altitudes, the coverage probability $P_c(\gamma)$ shows similar results against the power control factor ϵ where the coverage probability of the UAV increases exponentially as the height increases, and the UAV power decreases gradually after a spontaneous rise.
- Also, it was observed that for each of the UAV heights, the UAV power became constant at a 0.05 power factor for some time before a drastic fall to 0.1.
- It was also observed that $P_c(\gamma)$ increases progressively even for all attitudes with specific power control factor ranges, indicating that the UAV DL transmit power is small and is incomparable with the DL noise.
- As d increases, $P_c(\gamma)$ increases and is evidence for good network coverage for UEs with reduced path loss.

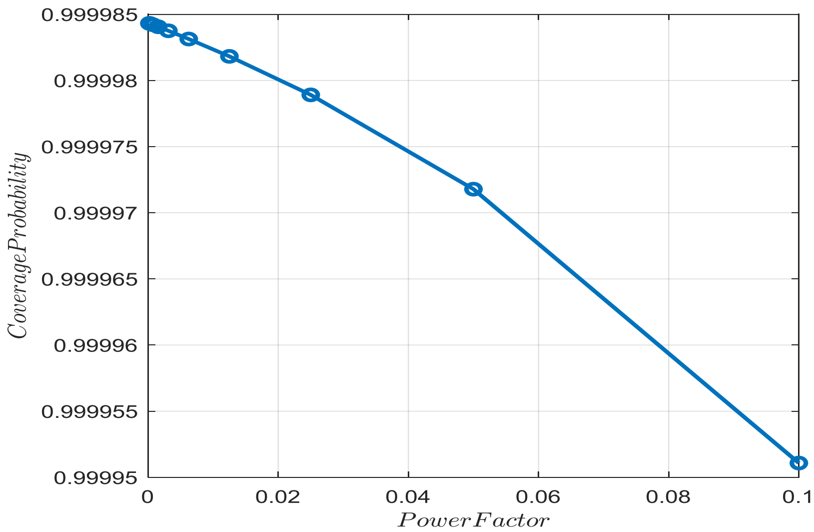


Figure 4: Coverage probability and power factor with a UAV distance of 200 m

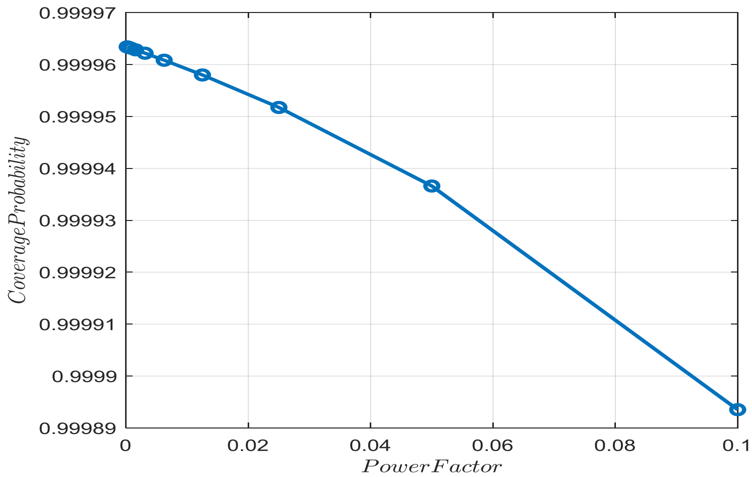


Figure 5: Coverage probability and power factor with a UAV distance of 300 m

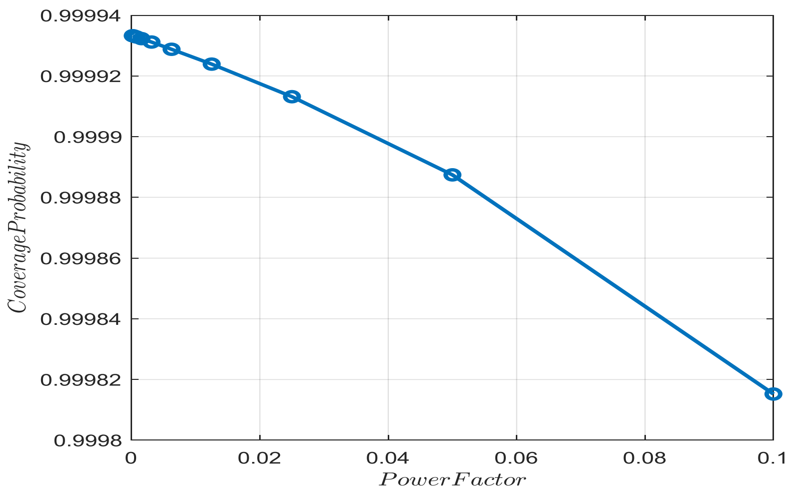


Figure 6: Coverage probability and power factor with a UAV distance of 400 m

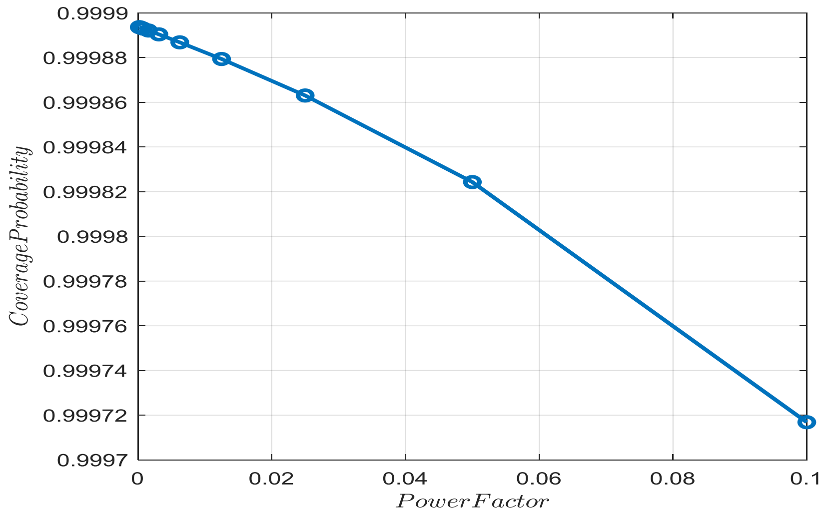


Figure 7: Coverage probability and power factor with a UAV distance of 500 m

3.2 Spectral Efficiency

Equation (6) shows that the spectral efficiency is dependent on the coverage probability, resulting in the spectral efficiency exhibiting the same changing effect as the coverage probability.

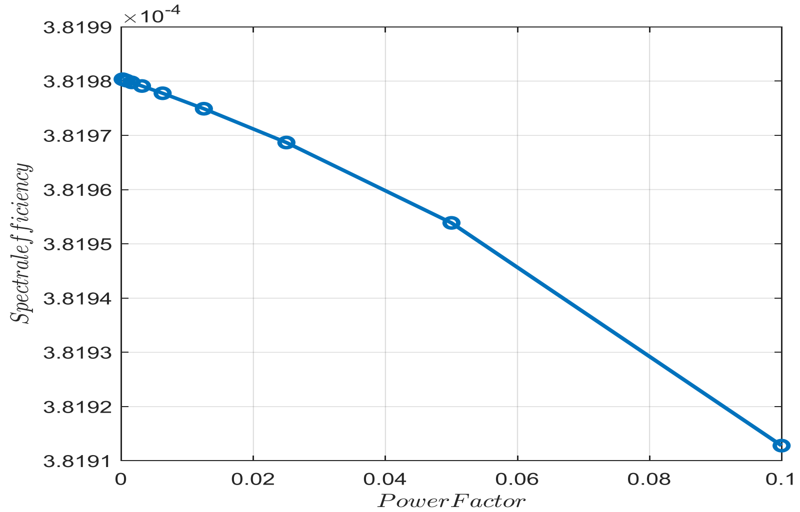


Figure 9: Spectral efficiency against the power factor

Hence, Figure 9 shows that the changes in the UAV's altitude, as presented, did not affect its efficiency level; thus, the spectral efficiency maintained an acceptable quality of service with power factor during the transmission.

5. Conclusion and Recommendation for further studies

In light of the anticipated advancements of 6G technology, this study has explored the crucial role of UAV integration in achieving seamless network connectivity. We specifically looked into what happens when the power control factor is lowered and how it affects the coverage probability and spectral efficiency of UAV downlink transmission in a heterogeneous network setting, which is like the future 6G era.

The analysis revealed significant findings regarding the coverage probability of the UAV. As the UAV's altitude increases, the coverage probability demonstrates an exponential growth trend. Simultaneously, the UAV power exhibits a gradual decrease after experiencing an initial spontaneous rise. Notably, for each UAV altitude, the UAV power stabilizes at a specific power control factor of 0.05 for a considerable duration before experiencing a sudden drop to 0.1. Even with these changes, the spectral efficiency stayed at a good level of quality of service, showing that the modified power control factor is strong enough to keep communication working well.

In the end, our study adds a lot to what we know about UAV downlink transmission in 6G networks. It shows what factors affect coverage probability and spectral efficiency with a lower power control factor. As 6G evolves, addressing UAV power sustainability and exploring adaptive power control mechanisms are pivotal in realizing the full potential of UAV integration in future wireless systems. By delving into these research areas, we can pave the way for a seamless and efficient 6G network ecosystem, empowering transformative applications and services that will shape the future of wireless communication.

5.0 Conflict of Interest

Conflict of Interest: The authors declare that they have no conflicts of interest.

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