SINR Coverage Enhancement of 6G UAV-Assisted Networks Deploying IRS

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1. Introduction

Sixth-generation wireless network will incorporate localization or sensing [1-20], terahertz-band signal [21-33], and various transmission technologies [34-50], etc. UAVs have attracted a lot of interest for a variety of potential applications. Several of the most intriguing application fields are UAV-enabled connectivity [51]. UAVs can serve as airborne base stations (BSs) to deliver wireless transmission services.

IRS has evolved as a disruptive innovation, intending to control the propagation situation during wireless transmissions [52]. IRS is a medium that allows the modification of impinging transmitted signals to enhance coverage to the cell edge. The IRS concept is founded on the notion of controlling the environment through the reflection of impinging received signals and the alteration of their phase shifts.

However, UAV-aided transmissions confront coverage and connection challenges, particularly in urban areas [53]. Infrastructures, trees, vehicles, etc. may still obstruct UAV communication links to users in a coverage area.

To solve these issues, IRS-assisted UAV communications [54] have recently been envisioned as a technique to avoid barriers and improve connectivity in UAV systems. An obstructed transmission link can be repealed using the IRS by constructing several LoS links, which considerably minimizes channel attenuation.

The research aims to enhance or maximize the coverage probability of a conventional UAV-assisted communication deploying IRS. The work compares the performance of an IRS-empowered UAV-assisted communication model with a conventional UAVaided model considering 2 GHz and millimeter wave (mmWave) carriers varying the network parameters.

2. Related Literature

The work included a review of prior literature relative to UAVassisted networks in this section.

Mahmoud et al. [55] investigated the deployment of IRS in UAV-empowered wireless communications aiming to improve the coverage of the Internet of Things (IoT) services. The work measured and compared the ergodic capacity, symbol error rate (SER), and outage probability in terms of conventional UAVaided communications and IRS-assisted UAV communications. The results show that IRS enhances the SER, ergodic capacity, and outage performance significantly. Liu et al. [56] analyzed the downlink coverage performance of IRS-UAV-empowered nonorthogonal multiple access (NOMA) communications network. The work aimed to efficiently allocate transmit power to UAVs and users to satisfy a flexible and ubiquitous NOMA transmission. Solanki et al. [57] investigated the performance of an IRSassisted NOMA transmission system, where the transmission of the base station (BS) is assisted by an IRS-assembled UAV. The work analyzed the outage probability of the transmission system. Wei et al. [58] performed sum rate maximization deploying IRS in UAV-assisted orthogonal frequency division multiple access (OFDMA) transmission system. Results derived that the employment of an IRS notably increases the sum-rate of UAVassisted communication systems. However, this research as well exempted coverage probability analysis. Mozaffari et al. [59] proposed and analyzed a framework for delay-aware cell association in UAV-assisted wireless networks. However, the work exempted the deployment of the IRS.

3. Measurement Model

In the case of a conventional UAV-assisted communication model [59], a set of UAVs are deployed alongside ground base stations (macro and micro) to enhance the network services for user devices (UD). This work considered an IRS-enhanced UAV-assisted wireless network in which the micro base station is serving the users through an IRS embedded with a UAV for an enhanced coverage.

A. Conventional UAV-Assisted Network

In this case, the downlink received power by the users from the serving UAV is measured as follows (Eq. 1) [59], [60],

$$\mathsf{P}_{r\in j}^{D(Conv.)} = \frac{\mathsf{P}_{t\in j}^{UAV}}{\mathsf{K}_0\mathsf{d}_i^2\mu} \tag{1}$$

where $\mathsf{P}_{t\in j}^{UAV}$ is the downlink transmit power of the serving UAV *j*. $\mathsf{K}_0 = \left(\frac{4\pi f_c \mathsf{d}_0}{c}\right)^2$. *c* is indicating the propagation velocity of light in ms^-1 . f_c is the frequency of the transmitted signal in Hz. d_0 is the reference free space separation distance between transmitter (UAV) and receiver (user) and $\mathsf{d}_0=1$ m. $d_i = \sqrt{(x^{UAV} - x^{UD})^2 + (y^{UAV} - y^{UD})^2 + (z^{UAV} - z^{UD})^2}$ denotes the separation distance between the serving UAV at

 $(x^{UAV},y^{UAV},z^{UAV})$ and the ground user devices located at

 (x^{UD},y^{UD},z^{UD}) coordinates. μ denotes the attenuation factor.

The reference works [59] and [60] considered the transmit power of UAV, $\mathsf{P}_{t\in j}^{UAV} = 0.5$ and 1 W respectively, carrier frequency, $f_c = 2$ GHz, UAV's altitude, $z^{UAV} = 200$ m, and $\mu = 3$ dB.

The downlink SINR can be calculated by the following equation (Eq. 2),

$$\mathsf{S}_{r\in j}^{D(Conv.)} = \frac{\mathsf{P}_{r\in j}^{D(Conv.)}}{\sum \mathsf{P}_{r\in i} + N_0} \tag{2}$$

where $\sum \mathsf{P}_{r \in i}$ is the total interference received by the user devices. $N_0 = -90$ dBm is the noise power.

B. IRS-Empowered UAV-Assisted Network

In the case of an IRS-UAV network, the downlink signal power received by the user devices is calculated by the equation below (Eq. 3) [61],

$$\mathsf{P}_{r\in j}^{D(IRS)} = \frac{\mathsf{d}_x \mathsf{d}_y \lambda^2 \mathsf{M}^2 \mathsf{N}^2 \mathsf{G}_t \mathsf{G}_r \mathsf{G}_{Sct.} cos\theta_t cos\theta_r \mathsf{A}^2}{(d_1 d_2)^2 64\pi^3} \mathsf{P}_{t\in j}^{BS-IRS} \qquad (3)$$

where $\mathsf{P}_{t\in j}^{BS-IRS}$ is the base station-to-IRS (attached with UAV) transmit power. d_x and $\mathsf{d}_y = \lambda/2$ represent IRS scattering elements length and width. The wavelength of the signal is λ . M and N denote the numbers of transmitter-receiver elements in IRS. The scattering gain of IRS is $G_{Sct.} = \frac{d_x d_y 4\pi}{\lambda^2}$. G_t and G_r are the transmitter-receiver gains. The transmitter (micro base station-to-IRS) and receiver (IRS-to-UD) angles are θ_t and θ_r . The amplitude of the reflection is denoted by A^2 .

$$d_1 = \sqrt{(x^{BS} - x^{IRS})^2 + (y^{BS} - y^{IRS})^2 + (z^{BS} - z^{IRS})^2}$$

is the micro base station-to-IRS (attached with UAV) separation where (x^{BS}, y^{BS}, z^{BS}) and $(x^{IRS}, y^{IRS}, z^{IRS})$ are the coordinates, respectively.

$$d_2 = \sqrt{(x^{IRS} - x^{UD})^2 + (y^{IRS} - y^{UD})^2 + (z^{IRS} - z^{UD})^2}$$

is the IRS-to-UD separation where $(x^{IRS}, y^{IRS}, z^{IRS})$ and

 (x^{UD},y^{UD},z^{UD}) are the coordinates, respectively.

The downlink SINR in the case of an IRS-assisted UAV communication network is obtained by the following equation (Eq. 4),

$$\mathsf{S}_{r\in j}^{D(IRS)} = \frac{\mathsf{P}_{r\in j}^{D(IRS)}}{\sum \mathsf{P}_{r\in i} + N_0} \tag{4}$$

C. Probability of Coverage

The user devices are said to be within the coverage of a UAV if the downlink SINR exceeds the selected threshold SINR.

Theorem: The probability of coverage [62] is denoted by (Eq. 5),

$$\mathcal{P}_{cov} = 1 - \sum_{j \in \mathcal{K}} \lambda_j \int_{R^2} exp\left(-\left(\frac{\mathsf{S}_j^{Thr.}}{\mathsf{P}_{t \in j}}\right)^{\frac{2}{\alpha}} \|q_j\|^2 \sum_{i=1}^K \lambda_i\right)$$

$$\mathsf{P}_{t \in i}^{\frac{2}{\alpha}} \times exp\left(-\frac{\mathsf{S}_j^{Thr.}}{\mathsf{P}_{t \in j}} \|q_j\|^2\right) dq_j$$
(5)

where λ_j denotes the density of the UAVs. $S_j^{Thr.}$ is the SINR threshold. $P_{t\in j}$ is the transmit power of the serving UAV (conv. model)/micro base station (IRS-UAV model). λ_i denotes the density of the interfering base stations. $P_{t\in i}$ indicates the transmit power of the interfering base stations. σ^2 is the noise variance. q_j denote the transmitter-receiver separation. α is the signal attenuation factor.

Proof: According to the definition of the probability of coverage (Eq. 6),

$$\mathcal{P}_{cov} = 1 - \mathbb{E}\left[\left(\bigcup_{j \in \mathcal{K}} \bigcup_{q_j \in \phi_j} SINR > \mathsf{S}_j^{Thr.}\right)\right]$$
(6)

where Eq. 6 is formulated considering the union bound and exploiting the Campbell Mecke Theorem [62] it can be represented as (Eq. 7),

$$\mathcal{P}_{cov} = 1 - \sum_{j \in \mathcal{K}} \lambda_j \int_{R^2} \mathbb{E} \left[\mathbb{P} \left(\frac{\mathsf{P}_{t \in j}}{\|q_j\|^{\alpha}} > \mathsf{S}_j^{Thr.} . I_{q_j} \right) \right] dq_j \quad (7)$$

where I_{q_j} denotes the interference.

Solving for (Eq. 8),

$$\sum_{j \in \mathcal{K}} \lambda_j \int_{R^2} \mathbb{E}\left[\mathbb{P}\left(\frac{\mathsf{P}_{t \in j}}{\|q_j\|^{\alpha}} > \mathsf{S}_j^{Thr.}.I_{q_j} \right) \right] dq_j \tag{8}$$

Since the propagation link is following Rayleigh fading-related distribution the equation becomes (Eq. 9),

$$\sum_{j \in \mathcal{K}} \lambda_j \int_{R^2} \mathcal{L}_{I_{q_j}} \left(\frac{\mathsf{S}_j^{Thr.}}{\mathsf{P}_{t \in j}} \right) exp \left(\frac{\mathsf{S}_j^{Thr.} \sigma^2}{\mathsf{P}_{t \in j} \|q_j\|^{-\alpha}} \right) \tag{9}$$

where $\mathcal{L}_{I_{q_j}}$ (.) represents the interference in a Laplace transformed form. Since the tiers of the considered network are selfsufficient or independent (Eq. 10),

$$\mathcal{L}_{I_{q_j}}(s) = \mathbb{E}\left[exp\left(-s\frac{\mathsf{P}_{t\in j}}{\|q_j\|^{\alpha}}\right)\right]$$
$$=\prod_{j\in\mathcal{K}}\mathbb{E}\left[\prod_{q_j\in\phi_j}exp\left(-s\frac{\mathsf{P}_{t\in j}}{\|q_j\|^{\alpha}}\right)\right]$$
(10)

Since the propagation channels are following Rayleigh distribution the formula of Eq. 10 becomes (Eq. 11),

$$=\prod_{j\in\mathcal{K}}\mathbb{E}\left[\prod_{q_j\in\phi_j}\mathcal{L}_{I_{q_j}}\left(\frac{\mathsf{P}_{t\in j}}{\|q_j\|^{\alpha}}\right)\right]$$
(11)

Applying the Poisson Point Process-aware Probability Formulating Function (Eq. 12),

$$= \prod_{j \in \mathcal{K}} exp\left(-\lambda_j \int_{R^2} \left(1 - \mathcal{L}_{I_{q_j}}\left(\frac{\mathsf{P}_{t \in j}}{\|q_j\|^{\alpha}}\right)\right) d_{q_j}\right)$$
$$= \prod_{j \in \mathcal{K}} exp\left(-\lambda_j \int_{R^2} \left(1 - \frac{1}{\left(1 + s\frac{\mathsf{P}_{t \in j}}{\|q_j\|^{\alpha}}\right)}\right) d_{q_j}\right)$$
(12)

Deploying Euler's Beta function and deriving the Polar coordinates from the Cartesian coordinates (Eq. 13),

$$\mathcal{L}_{I_{q_j}}(s) = exp\left(-s_{q_j}^{\frac{2}{\alpha}}\sum_{j\in\mathcal{K}}\lambda_j\mathsf{P}_{t\in j}^{\frac{2}{\alpha}}\right)$$
(13)

Using Eq. (9) and (13) the coverage probability can be written as follows (Eq. 14),

$$\mathcal{P}_{cov} = 1 - \sum_{j \in \mathcal{K}} \lambda_j \int_{R^2} exp\left(-\left(\frac{\mathsf{S}_j^{Thr.}}{\mathsf{P}_{t \in j}}\right)^{\frac{2}{\alpha}} \|q_j\|^2 \sum_{i=1}^K \lambda_i\right)$$

$$\mathsf{P}_{t \in i}^{\frac{2}{\alpha}} \times exp\left(-\frac{\mathsf{S}_j^{Thr.}}{\mathsf{P}_{t \in j}} \|q_j\|^2\right) dq_j$$
(14)

Corollary: The probability of coverage can be simplified as (Eq. 15),

$$\mathcal{P}_{cov} = 1 - exp\left(-\pi \mathsf{S}_{r\in j}^{D\frac{2}{\alpha}} \frac{\lambda_j \mathsf{S}_j^{Thr.\frac{-2}{\alpha}}}{\sum_i \lambda_i}\right) \tag{15}$$

where $\mathsf{S}_{r\in j}^D$ is the downlink SINR.

4. Numerical Results and Discussions

This section contains the numerical results derived by the equations stated in the previous section utilizing MATLAB. This work considers that the micro base stations are serving/feeding the IRS (passive reflector) attached to UAV with communication facilities to enhance the overall network coverage for users, especially cell-edge users. The reference works [59] and [60] considered that the UAV serves to extend the coverage for the user performing like a coverage extender (controlled by ground base stations). Table 1 states the measurement parameters and values.

Fig. 1 (a), (b), (c), and (d) represent the comparative coverage probability performance analysis for the conventional and IRS-assisted UAV communication model in terms of varied measurement parameters.

Fig. 2 (a), (b), (c), and (d) illustrate the coverage probability measurements for the conventional UAV-assisted communication model for multiple mmWave carriers in terms of varied measurement parameters.

Fig. 3 (a), (b), (c), (d), (e), and (f) visualize the coverage probability measurements for the IRS-enhanced UAV-aided

| Parameters | Values |
|-------------------------------------|--------------------------------------|
| Macro cell area | 1000x1000m |
| Micro cell area | 200x200m |
| Macro BS power | 30 W |
| Micro BS power | 8 W |
| Micro BS power (to IRS) | 0.1, 0.2, 4 W |
| UAV transmit power (Conv. Model) | 6 W, 8 W |
| Macro BS height | 20 m |
| Micro BS height | 10 m |
| UAV altitude | 50, 100, 200 m |
| Carrier frequencies | 2, 30, 55, 80, 100 GHz |
| Tx-Rx elements | 32, 64, 128, 256 |
| Tx-Rx gain (IRS) | 20 dB [63], 14 dB [64] |
| Transmit-receive angles | 45° |
| Density of IRS | $1000/(\pi(100)^2) \text{ per } m^2$ |
| Density of Micro BS | $1000/(\pi(100)^2) \text{ per } m^2$ |
| Density of Macro BS | $(1000/(\pi(100)^2))/5$ per m^2 |
| Amplitude of reflection | 0.9 |
| Attenuation exponent | 2 |

Table 1: Measurement Parameters and Values



(a)





(c)



(d)

Figure 1: (a) Comparison of the coverage probabilities (transmit power 0.5 W, 1 W, 0.1 W, transmitter-receiver/IRS elements = 32, UAV altitude = 200 m), (b) Comparison of the coverage probabilities (transmit power 0.5 W, 1 W, 0.2 W, IRS elements = 32, UAV altitude = 200 m), (c) Comparison of the coverage probability (transmit power 0.5 W, 1 W, 0.2 W, IRS elements = 32, UAV altitude = 100 m), (d) Comparison of the coverage probability (transmit power 0.5 W, 1 W, 0.1 W, IRS elements = 64, UAV altitude = 200 m).



(a)







(c)



Figure 2: (a) Coverage probability for conventional UAV model (6 W, UAV altitude = 100 m), (b) Coverage probability for conventional UAV model (8 W, UAV altitude = 100 m), (c) Coverage probability for conventional UAV model (6 W, UAV altitude = 50 m), (d) Coverage probability for conventional UAV model (8 W, UAV altitude = 50 m).

communication model for multiple mmWave carriers in terms of varied measurement parameters.



According to the observation of Fig. 1 (a) containing the comparative analysis among references [59] and [60] and this work, the research derived that the IRS-empowered UAV-aided communication performs better with a reduced transmit power (0.1 W) compared to the conventional UAV model. The IRS-UAV model can tolerate up to 9 dB of the SINR threshold for a coverage probability of 0.55-0.6 (denoting a median or moderately favorable coverage). On the contrary, in the case of the





(c)



Figure 3: (a) Coverage probability for IRS-UAV model (4 W, IRS elements = 128, UAV altitude = 100 m), (b) Coverage probability for IRS-UAV model (4 W, IRS elements = 128, UAV altitude = 50 m), (c) Coverage probability for IRS-UAV model (4 W, IRS elements = 256, UAV altitude = 100 m), (d) Coverage probability for IRS-UAV model (4 W, IRS elements = 256, UAV altitude = 50 m).

conventional UAV model presented in the reference works [59] and [60], respectively, 1 and 4 dB of the SINR threshold is tolerable in terms of the considered moderate or median level of coverage probability of 0.55-0.6. According to the realization of Fig. 1 (b) in the case of the IRS-UAV model if the transmit power is increased (from 0.1 W to 0.2 W) the transmission can tolerate a bit high SINR threshold i.e., up to 12 dB. From the observation of Fig. 1 (c), it is comprehensible that, if the altitude of the UAV is reduced (from 200 m to 100 m) the SINR performance improves a bit. In this case, the tolerable SINR thresholds are 6 [59], 9 [60], and 20 dB (this work). As per the realization of Fig. 1 (d), in the case of an IRS-UAV model with a transmit power of 0.1 W or 100 mW and a 200 m of UAV altitude increasing the number of elements of IRS (from 32 to 64) can enhance the tolerable SINR threshold up to 21 dB.

Since the work performed further measurements considering mmWave carriers it considered a reduced altitude of UAV with an increased power compared to the reference works [59] and [60]. Observing Fig. 2 (a) it is comprehensible that, with 6 W of transmit power and 100 m altitude of the UAV the performance of the conventional UAV is not satisfactory. In this case, the considered mmWave carriers require a very lower level of SINR threshold (-10 to 0 dB) to obtain a coverage probability of 0.55-0.6 which is not feasible in a wireless communication system. The performance is not satisfactory even with an increased transmit power of UAV, i.e., 8 W when UAV altitude is the same as previous according to Fig. 2 (b). According to the observation of Fig. 2 (c), with a reduced altitude of UAV, i.e., 50 m and 6 W of transmit power 30 GHz mmWave band can tolerate up to 2 dB of SINR threshold. However, the SINR performances of other carriers are still below the satisfactory level (-8 to -3 dB SINR threshold is required for 55, 80, and 100 GHz carriers for coverage probability of 0.55-0.6). Analyzing Fig. 2 (d) it is realizable that, with an increased transmit power of the UAV, i.e., 8 W and 50 m altitude the performance of the 30 GHz carrier improves a bit (up to 4 dB SINR threshold is tolerable). However, in this case, as well the performances of higher level mmWave carriers, e.g., 50, 80, and 100 GHz cannot be considered satisfactory (-7 to -2 dB SINR threshold is required for coverage probability of 0.55-0.6). Since the evolving 6G networks have to feature significantly higher data rates, extremely low latency, and significant reliability this kind of SINR performance of the mmWave carriers is not favorable to ensure efficient coverage to the 6G high-end user devices.

As per the interpretation of Fig. 3 (a) it is realizable that, according to the measurement parameters (4 W, IRS elements =

128, UAV altitude = 100 m) 30 GHz mmWave band exhibits better SINR performance (can tolerate up to 8 dB of SINR threshold for a coverage probability of 0.55-0.6). However, the SINR performances of other carriers are still below the satisfactory level (-12 to -2 dB SINR threshold is required for 55, 80, and 100 GHz carriers for a coverage probability of 0.55-0.6). Reduction of the UAV altitude (50 m) enhances the performance a bit namely 30 GHz can tolerate up to 14 dB of SINR threshold, 55 GHz can tolerate up to 3 dB of SINR threshold, and the performance of 80 and 100 GHz carriers still below satisfactory level according to Fig. 3 (b). With a transmit power of 4 W, 256 transmitter-receiver elements of IRS, and 100 m of altitude of UAV 30, 55, 80, and 100 GHz carriers can tolerate up to 20, 10, 3, and 0 dB of SINR thresholds, respectively, in terms of coverage probability of 0.55-0.6 by the observation of Fig. 3 (c). Analyzing Fig. 3 (d) it is comprehensible that, with a transmit power of 4 W, 256 transmitter-receiver elements of IRS, and 50 m of altitude of UAV 30, 55, 80, and 100 GHz carriers can tolerate up to 26, 15, 9, and 5 dB of SINR thresholds, respectively, in terms of coverage probability of 0.55-0.6.

5. Conclusion

The research aimed to enhance the SINR coverage performance

of a UAV-assisted wireless communication system deploying IRS. The work described several prior works to reflect the current research directions relative to this research issue. It formed a measurement model including the equations relative to the targeted measurement in the context of both conventional and IRS-UAV communication models. Afterward, the research analyzed and compared both of the models utilizing computer-aided measurement with MATLAB. The work derives that the deployment of IRS significantly enhances the performance of a UAV-assisted wireless network with a notable minimization of energy consumption.

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