Design Feasibility and Link Budget Assessment of Aerial 5G IoT and eMBB Connectivity

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***Abstract*—Uncrewed Aerial Vehicles (UAVs) equipped with radios can establish rapid, ad-hoc connectivity in areas where terrestrial infrastructure is unavailable or compromised. Leveraging the virtualized architecture of Fifth Generation (5G) mobile networks, both base station and required minimal core functions can be hosted aloft, enabling agile IoT or eMBB centric private networks for emergency response, expeditionary, military operations, and consumer events. This study evaluates the technical feasibility of UAV-mounted 5G Non-Public Network assembled from commercial off-the-shelf components, comparing the physical radio layer performance of IoT and evolved mobile broadband use cases. Candidate 3GPP architectural options are reviewed, and radio link budget calculations quantify physical layer performance in open and rural environments for a single-UAV. The obtained results highlight the trade-off between frequency band, UAV-altitude, and the resulting radio coverage and data rate, providing design guidance for lightweight, energy-efficient aerial 5G systems.**

Keywords-aerial 5G network; link-budget analysis; uncrewed aerial vehicle (UAV); non-public network (NPN); drone-mounted IoT and eMBB radio service; emergency communications; ad-hoc radio access network (RAN).

I. Introduction

Apart from their commercial use, cellular systems can be deployed also as complementing ad-hoc networks, e.g., in emergency solutions after a natural disaster that has damaged telecommunications infrastructure, or in scenarios where non-permanent augmented capacity and radio coverage are desired. A Fifth Generation (5G) private mobile network model through temporally deployed base stations can provide a suitable platform for data transfer and signaling in such situations, enabling enhanced communications and situation awareness also for, e.g., defense groups.

However, in temporal ad-hoc use cases, 5G users may be highly mobile, so deploying terrestrial trailer-mounted radio base stations may not suffice, as the varying link conditions alter quality and can result in uncertainties, resulting in radio network outages when users are on the move. An aerial ad-hoc 5G network that follows the underlying users can provide an important opportunity to overcome these challenges.

3GPP is developing the Internet of Things (IoT) concept further in 5G as a logical continuum from the 4G era, in terms of massive Machine Type Communications (mMTC). 5G IoT in 3GPP is realized through legacy Long-Term Evolution (LTE) -based Narrow-Band IoT (NB-IoT) and LTE for Machines (LTE-M) seamlessly attached to the 5G Core Network (CN) and, from Release 17 onward, through 5G New Radio (NR) RedCap, which is a native, reduced-bandwidth flavor of NR, and evolves further as of Release 18 [1]. Combining Non-Public Network (NPN) and IoT through aerial platform enables novel means to develop and provide low-power, low-data rate services in very large areas.

This paper presents a feasibility study of a UAV-based 5G radio network that can be used in various Line of Sight (LOS) scenarios through 5G NPN. Section II discusses the state-of-the art of UAV-assisted wireless communication and current gaps. Section III presents IoT and eMBB, and Section IV discusses 3GPP-defined 5G NPN. Section V describes a 5G-UAV concept and discusses UAV-mounted equipment, presenting an example of a feasible set. Section VI describes physical radio aspects, and Section VII presents the results obtained for validation of radio network performance applying adequate radio propagation modeling for aerial network, comparing 5G eMBB and IoT use cases that represent two “extremes” in terms of achievable 3D-network coverage areas. Finally, Section VIII summarizes the findings, and Section IX presents the plan for further research.

The novelty of this research lies in the following: 1) it presents a concept based on 3GPP-defined NPN-architecture and available Commercial Off-the-Shelf (COTS) components to provide aerial IoT and data services to a variety of use cases and 2) it evaluates performance of such a solution comparing UAV-mounted 5G gNB performance of eMBB and mMTC.

This study considers single UAV for local communication to a set of User Equipment (UE) underneath, paving the way for the forthcoming work that will consider the formation of a multi-UAV-based 5G RAN service and automized location functions through advanced sensing and artificial intelligence.

II. UAV-Assisted Networking

The global 5G deployments are expanding. The GSM Association (GSMA) estimates that the adaption for 5G will surpass that of 4G in 2028, whereas the earlier networks, 2G and 3G, keep losing their customers; in fact, many of these networks have already been decommissioned [2]. The current 5G system architecture models enable various deployment options and variations for tailored solutions. Examples of these facilitators include new NPN architectures, non-terrestrial networks (NTN), Open RAN, and mMTC, that are evolving and being deployed in commercial networks.

While 5G matures, there are already concrete efforts to develop systems beyond 5G (B5G), paving the way for Sixth

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Generation (6G) [3]. During Release 20, 3GPP has carried out use case and feasibility studies, and the actual forming of technical 6G specifications begins along with the Release 21. The first commercial 6G networks can be expected to be available as of 2030 [4]. The 6G is anticipated to be particularly attractive for connected UAVs due to significant improvements, including ubiquitous 3D connectivity on the ground and in the air [5].

While 6G is still under development, the current 5G systems outperform the previous generations, and can be tailored to provide radio service also beyond traditional terrestrial base stations through Service-Based Architecture (SBA) and Service-Based Interfaces (SBI) that handle specific needs of varying use cases and dynamically provide optimal sets of required and available resources to different usage types through Network Functions Virtualization (NFV).

The key benefit of 5G is its ability to run Network Functions (NF) on COTS hardware. This evolution makes 5G a suitable candidate also for UAV-type networking, e.g., through non-public network models as they can form an architectural base for isolation (with augmented security) or interconnection / roaming (providing wider connectivity) network segment. A Mobile Network Operator (MNO) or Network Slice (NS) Provider (NSP) can set up NSs, that can be used for deploying UAV-networks, too.

5G systems can be optimized further through Open RAN (Radio Access Network). Examples of the efforts driving Open RAN include Open RAN Alliance's O-RAN [6] and Telecom Infra Project's TIP [7]. Via Open RAN, vendor-specific internal RAN interfaces are opened so that an extended number of stakeholders can provide select RAN protocol layers independently, increasing efficiency and reducing costs [8], and it can be used also in UAV-based networking [9].

As for the State of the Art and challenges, the mobile networks' radio coverage extension mounting a base station or repeater on aerial vehicle has been studied from several points of view, such as how to maximize the radio coverage by optimal UAV positioning [10] and how to enable group handover for drone base stations [11] related to the mMTC, use of data services, and commercial needs for respective coverage and capacity extension to facilitate adequate data rates and Quality of Service (QoS) for the subscribers.

On radio link budget, there are various studies such as [12] (high-altitude platform for 5G access node) and [13] (system model for forward link transmissions in an Integrated Access and Backhaul IAB multi-tier drone cellular network). An example of real-world UAV-based networking is AT&T's 5G Cell on Wings (CoW), a drone-mounted cellular 4G or 5G base station that temporarily extends radio coverage, e.g., during disasters and large events [14].

Nevertheless, the available studies are not necessarily conclusive in terms of the tradeoffs of the UAV altitude and wider set of deployed frequency bands [15]. Furthermore, the adaptation of optimal architectural models of UAV-networking, considering the feasibility and gaps of COTS components, can benefit from additional research [16].

TABLE I. COMPARISON OF KEY ASPECTS OF 5G EMBB AND IOT

Item	eMBB	IoT
Channel bandwidth	20 – 400 MHz	180 kHz – 20 MHz
SNR (BLER<10%)	8 – 15 dB (64 / 256 QAM)	-13 – -3 dB (BPSK / QPSK, heavy coding)
Fade/penetr. marg.	3 – 5 dB	10 – 15 dB
Device TX power	23 dBm (smartphone)	14 – 23 dBm (sensor)
Data rate target	10 Mb/s – 1 Gb/s	50 b/s – 1 Mb/s

TABLE II. PRIVATE NETWORK TYPES IN UAV-BASED DEPLOYMENTS

Variant	Assessment
SNPN (fully standalone architecture)	Best for autonomous, localized, quick-to-deploy networks (no MNO dependency)
PNI-NPN with radio access network sharing	Enables UAVs to share ground RAN where available, while maintaining separate core
PNI-NPN with core network sharing	UAV-based NPN reuses public 5G core network, allowing leaner deployment
UE route selection via mobile network selection	UEs served by UAVs can select between private and public network profiles

III. IOT VS. EMBB

The 5G eMBB and IoT (mMTC) represent opposites in terms of many aspects, like data rates, power consumption and number of simultaneously communicating devices. These elements dictate also the achievable radio coverage area size. For example, IoT has been optimized for bandwidth given that IoT payloads are small, and narrow band lowers the thermal noise floor. IoT relies on robust modulation schemes and Hybrid Automatic Repeat Request (HARQ) repeats balancing respective throughput and coverage. It is important to note that battery-driven IoT modules stay below 1 W to meet license and life constraints (e.g., NB-IoT Class 3 and Class 5 use 23 dBm and 20 dBm, respectively). Table I summarizes some of the key differences of IoT and eMBB.

IV. AERIAL PRIVATE NETWORK CONSIDERATIONS

3GPP has designed private network realizations through Standalone Non-Public Network (SNPN) and Public Network Integrated Non-Public Network (PNI-NPN) models [17] as presented in Table II. Although 3GPP designed these models for terrestrial networking, their principles can be extended to serve also in aerial networks.

For the architectural modeling of 5G-based UAV network, the following technical specifications form the base: 1) 3GPP TS 23.501 (System Architecture for the 5G System) defines high-level architecture for both SNPNs and PNI-NPNs [18]; 2) 3GPP TS 23.548 (5G System Enhancements for NPN) explores enhancements specific to NPNs (e.g., management, registration, selection) [19]; and 3) 3GPP TS 22.261 (Service Requirements for 5G System) covers typical service-level requirements relevant to NPNs including verticals, e.g., public safety [20] stating also that 5G is expected to support various enhanced UAV scenarios for applications and scenarios for low altitude UAVs in commercial and government sectors.

SNPN is self-contained and independently operated from public networks. It is adequate for rapid deployment for on-

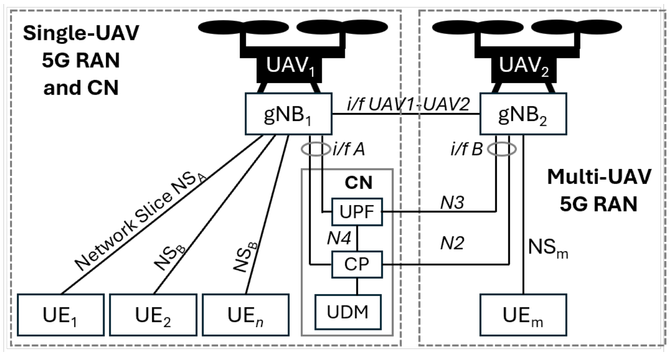

Figure 1. UAV-based, isolated SNPN realization; this feasibility study considers radio performance of a single 5G-UAV scenario

demand aerial networks with no dependency on commercial MNO infrastructure and is thus a match for UAV-based temporal networks serving field units. PNI-NPN, in turn, is an NPN deployed with integration into a public mobile network, and it may share infrastructure (e.g., RAN or core network). The variants of PNI-NPN include RAN-sharing with network slicing, core network sharing; and UEs with public and private subscriptions (PLMN/NSI selection).

Table II summarizes the 3GPP-defined NPN types and presents their key benefits related to their applicability for forming UAV-based network services.

V. 5G-Capable UAV Realization

A. Architecture

The system considered in this study is based on minimal viable 5G SNPN architecture and a single UAV equipped with a 5G gNB (gNode B) enabling local connectivity to the UEs underneath to provide temporarily deployable service if complementing MNO infrastructure is not available. Figure 1 presents the UAV-based SNPN realization in this study. UAV (or set of UAVs) can house radio functions, whereas the essential core network functions of gNBs can be implemented on the same UAVs, separate UAVs, or ground station.

This model can be extended to cover additional UAVs and respective gNBs that are interconnected (e.g., through low-latency PC5 link between vehicles) forming a 5G RAN drone swarm, e.g., via 5G-based mesh between UAVs.

In multi-UAV 5G radio service provisioning, it can be reasoned that maintaining optimal 3D placement is hard as small altitude shifts swing path loss and backhaul Signal-to-Noise Ratio (SNR), so sufficient overlapping must be ensured. Some additional challenges include satellite positioning jitter or denial that can degrade the Time Division Duplex (TDD) timing and node loss fragments control. To overcome these challenges, control can be made hierarchical (central planner and local packet core), and use of multi-source timing can help in this. The rapid geometry changes are another challenge as they may trigger ping-pong handovers, especially in the case of narrow NR beams that raise beam-failure risk in UAV turns. Also, a dominating cell with a weak multi-hop backhaul can impact negatively the Quality of Service (QoS).

TABLE III. Functional architecture of aerial 5G system

Layer	Function	Realization
Radio Access (RA)	gNB (5G standalone) with full UE-to-UE routing support	Lightweight COTS integrated into small cell
Control Plane (CP)	Lightweight distributed UAV logic (also swarm consensus)	Simple microcontroller and onboard logic
Backhaul (BH)	None (fully isolated); direct local P2P 5G	PC5 direct-mode or local user plane function (UPF)
Intelligence	Initially manual; advanced version has UE-following	Position, RSSI-based positioning heuristics
UE Signaling	Simple beaconing uplink from UEs, e.g., by Synchronization Signal Blocks (SSBs)	Existing 5G UE support
Swarm Comms	When more than one UAV, 5G-based mesh between UAVs	5G PC5 (Sidelink)

TABLE IV. Examples of 5G RAN key equipment per UAV (*power consumption estimated in typical average / peak watts)

Component	Description	Example	Weight	Power*
Integrated 5G Small Cell	Embedded gNB; RU (SA mode)	Amarisoft Callbox Mini / Baicells Nova430	400 – 800g	25 / 40W
Light Compute Module	For basic UAV / swarm logic	Raspberry Pi CM4 or Jetson Nano	100 – 200g	8 / 12W
Simple Mesh Swarm Radio	IEEE 802.11s Wi-Fi 6 / V2V PC5	Compex WLE900VX / 5G module	50 – 100g	6 / 12W
Battery Pack	Standard UAV LiPo	6S 22000 mAh	1.5 – 2.0kg	0.6 / 1W
Positioning Sensors	GPS, IMU	COTS GPS + Pixhawk FC	<100g	3 / 5W

To overcome this challenge, it is possible to apply larger handover hysteresis (e.g., 3-5 dB) and time to trigger (e.g., 160-320 ms), implement dual connectivity feature (make-before-break), and use backhaul-weighted cell selection.

B. Equipment Considerations

To deploy a 5G SNPN UAV RAN, the UAV can host a basic integrated gNB (e.g., Amarisoft / Parallel Wireless). The basic location management is assumed to be manual and satellite positioning system -assisted, but automated methods can also be developed based on UE signals and using basic Radio Frequency (RF) heuristics (e.g., weighting received signal strength indicator) to position the UAV(s) according to user density.

Basing the solution on COTS devices, Table III presents a set of feasible candidate elements for simplified functional architecture.

Table IV presents examples of UAV-mounted equipment. For advanced alignment of the UAVs and UEs, downward-facing cameras can be considered for UE clustering estimation (COTS-based image processing) and barometers for altitude stabilization. Based on the selected options minimizing the weight of the components, the total UAV payload (essential RAN components) is at minimum approximately 2.5–3.0 kg, which is feasible for medium-class UAVs (e.g., DJI Matrice 300 RTK [21] or similar custom UAVs).

One of the key challenges of UAV-based networking is the limitations of power supply, which represents the major weight of the payload. As an example, the above-mentioned DJI Matrice 300 RTK supports up to 55 minutes operational flight time [21]. For the communication components, Table IV presents a rough estimate of the average and peak power drain. As can be seen, the gNB consumes major part of the total power. For the operational power of the UAVs and 5G RAN components, this feasibility study assumes ideal power management, but in practice, hybrid model can be used with tethered UAVs (permanent anchor nodes with gNBs) and rotating UAVs (fly, recharge, rotate). Complementary power sources can be, e.g., solar panels (small flexible panels on UAV structure extending flight by approximately 10-20%), hydrogen fuel cells (about 2-3× endurance of lithium polymer, LiPo), or tethered power supply forming wired UAVs with unlimited power (for anchor UAVs [22]).

It should be noted that regulation limits the operational boundaries in terms of UAV altitude and maximum radiated power. As an example, there is no general airborne-gNB EIRP allowance in the USA and the power is what the experimental or carrier's license and service rules permit, often with tight coordination to prevent wide-area interference. US-rules dictate 400 ft for the maximum UAV altitude above ground level (AGL) under Part 107, although higher values can be permitted via waiver. In the EU, routine airborne gNBs are not covered by the standard local/private-5G licenses, so specific or certified flight approval is needed with EASA framework as well as a trial or temporary spectrum license from the national regulator, and the maximum altitude is 120 m AGL.

VI. Physical Radio Interface

This feasibility study considers theoretical coverage limits of a single UAV applying relevant propagation loss models, with the aim to provide optimal 5G RAN quality and performance as a function of UAV altitude (and later, inter-UAV distance) in rural and open areas, and the following parameters: 1) Frequency band f = low (1 GHz), mid (3.5 and 6 GHz) and high (24 and 28 GHz); 2) UAV altitude h_{gNB} = 50m, 100m,. . . , 400m; 3) UE type = pedestrian; 4) Power = P_{UE} +23 dBm, P_{gNB} +23 dBm; 5) UAV antenna type = omni-directional (0 dBi gain, uniform, ideal radiation pattern). The key results include achievable cell size and respective data rate estimate for both eMBB and IoT use cases.

The starting point of the study was to consider a single UAV that houses 5G SNPN equipment needed to form basic radio access for the UE-UAV$_{\mathrm{gNB}}$-UE communications.

In rural and open-space areas, for the line of sight (LOS) scenarios, the free space path loss L_{FSPL} (in dB) can be estimated by applying the ITU-R P.525 model (within version 12 of ITU-R P.1411) that assumes minimal obstructions [23]. The LOS path loss equation is:

$$L_{FSPL} = 20log_{10}f + 20log_{10}d + 92.45 \quad (1)$$

In this equation, f is the frequency in GHz and d is the distance in kilometers between UAVgNB and UE.

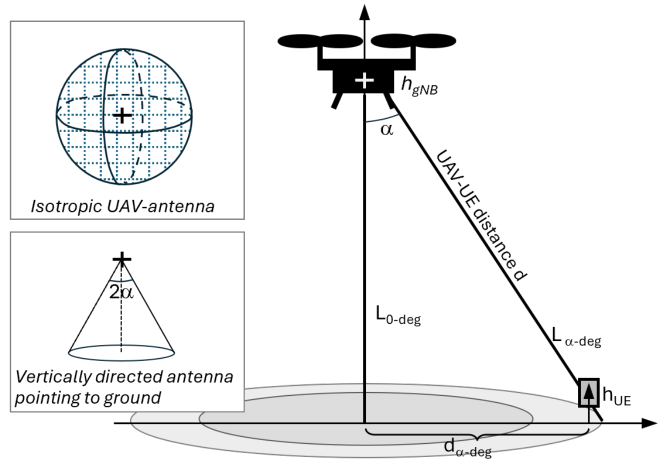

Figure 2. Principle of (theoretic) radiation patterns and respective radio coverage formation assumed in this study

In the feasibility study presented in this paper, Figure 2 depicts the principle of the UAV setup. For the baseline and comparative reference, this study is based on a theoretical omnidirectional UAV-mounted 0 dBi antenna. In practice, isotropic antenna gain is conservative whereas directive antenna enhances the link and optimizes the radio coverage also for minimizing the interference; an example of this is a cone-shaped vertical radiation pattern as depicted in Figure 2. In field deployments, an adaptive Multiple-In Multiple Out (MIMO) antenna provides augmented performance, capacity, and interference mitigation, but the drawback is the increased complexity and power consumption. To keep the antenna complexity and respective power consumption at minimum in this study, passive omni-directional approach provides means to materialize multi-UAV gNB connectivity without a need for a specific steering logic. In practice, for the final selection of the antenna type and respective gain, detailed radio network planning is important for ensuring adequate inter-UAV connectivity and radio cell dimensioning. The impact of the final antenna gain can be considered adjusting the presented GTX parameter values.

VII. Results

Using ITU-R P.1411, Figure 3 presents the path loss UE-UAV at a distance d from UAV's location for isotropic UAV TX antenna at 100 m altitude (earth curvature limit 35 km) for frequency bands 1 GHz – 28 GHz.

Considering the same frequency range 1 GHz – 28 GHz, Figure 4 summarizes the estimated path loss values L (dB) directly beneath (a=0º) and off the vertical location of the UAV (a=30º) in open and rural areas, when the UAV altitude varies between 50 m and 400 m. The presented LOS path-loss estimates show that the altitude-distance trends for 1–28 GHz match the 3GPP TR 38.901 LOS baseline [24]. Comparable UAV-gNB studies at 28 GHz [25] [12] show the same free-space path loss driven scaling, with practical shortfalls mainly from blockage, beam-pointing, and backhaul constraints rather

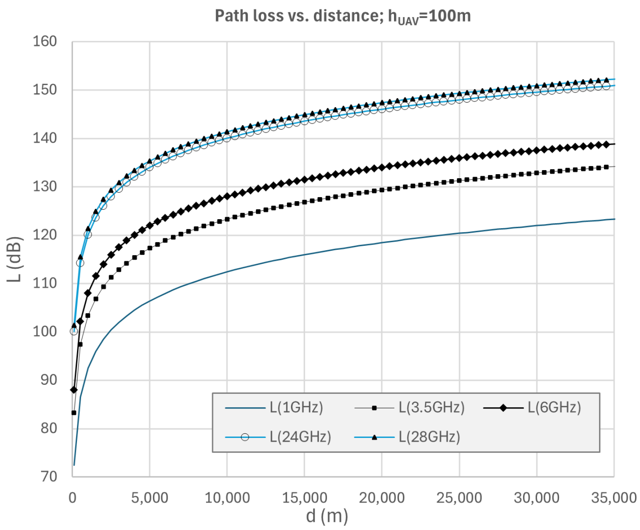

Figure 3. Path loss of UAV-UE as a function of the UE's distance from UAV's vertical reference location (UAV altitude is 100m)

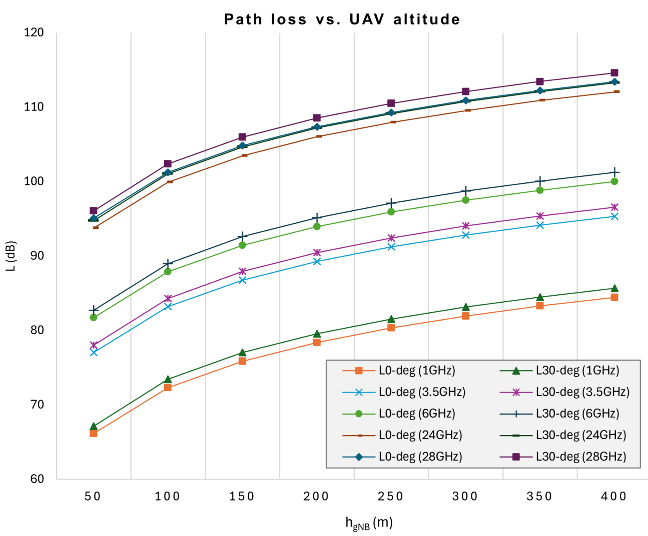

Figure 4. Path loss prediction, 1GHz–28GHz, for UAV altitudes of 50m–400m

than the LOS model itself. Consistent with geometry, off-nadir (30°) incurs about 1.25 dB extra loss from the longer slant range, and at 100 m altitude the footprint is curvature-limited. Deployment planning can thus start with FSPL-based bounds and subtract environment-specific losses for realistic coverage.

A. Scenario: eMBB

Table V presents the key eMBB radio budget items, and Table VI presents an example of the radio link budget when the UAV altitude is 400 m and the UE is located underneath.

In these scenarios, the channel bandwidth is 20 MHz (1 GHz), 100 MHz (3.5/6 GHz), or 400 MHz (24/28 GHz). In these calculations, spectral efficiency model is η (bps/Hz) = $0.6\times\log_2(1+\text{SNR})$. The assumption for the 0.6 factor is due to scheduler, modulator and coding inefficiencies that lower

TABLE V. Applied radio link budget items, eMBB scenario

Parameter	Value	Notes
gNB transmitter power P_{TX}	+23 dBm	Typical small-cell power limit, applicable to a UAV-mounted gNB
TX antenna gain G_{TX}	0 dBi	Isotropic (no beamforming)
UE antenna gain G_{RX}	0 dBi	Smartphone baseline
Fade margin M	3 dB	Covers body loss, ageing, fading
UE noise figure NF	7 dB	5G NR handset typical
Thermal noise density	–174 dBm/Hz	$N_o=kT=1.38\times10^{-23}$ J/K × 290K

TABLE VI. Example of the radio link budget (d=400m)

Link budget, h_{UAV}=400m, α=0º	**1 GHz**	**3.5 GHz**	**6 GHz**	**24 GHz**	**28 GHz**
Path loss PL, dB at (2km)	84.5	95.4	100.1	112.1	113.4
Tx power (gNB), dBm	23.0	23.0	23.0	23.0	23.0
Tx antenna gain, dB	0.0	0.0	0.0	0.0	0.0
UE antenna gain, dBi	0.0	0.0	0.0	0.0	0.0
Implementation/fade margin, dB	3.0	3.0	3.0	3.0	3.0
UE noise figure NF, dB	7.0	7.0	7.0	7.0	7.0
Thermal noise density, dBm/Hz	-174	-174	-174	-174	-174
Channel bandwidth, MHz	20	100	100	400	400
Received power Prx, dBm	-61.5	-72.4	-77.1	-89.1	-90.4
Noise floor N, dB	-94.0	-87.0	-87.0	-81.0	-81.0
Operational SNR after margin, dB	29.5	11.6	6.9	-11.1	-12.5
Spectral efficiency SE	5.88	2.38	1.54	0.06	0.05
Data rate, Mb/s	**117.6**	**237.5**	**154.4**	**25.8**	**19.1**

the theoretic capacity of Shannon limit. The received power is $P_{RX} = P_{TX} + G_{TX} + G_{RX} - L$, and the noise floor is N = -174 + 10 $\log_{10}B + NF$. The operational signal to noise ratio (SNR) after margin is SNR = $P_{RX} - N - M$. The spectral efficiency $SE = 0.6\times\log_2(1+10^{\text{SNR}/10})$, and the data rate is $R = SE \times B$. Beyond the presented calculations, the effective SINR enhances through beamforming gain G_{BF} that is typically 3-10 dB whilst the level of interference lowers it respectively. MIMO, in turn, adds rank often 1-2 aloft scaling efficiency, and resource allocation gives a per-UE share 0.3-0.8. [26]

Figure 5 and Figure 6 summarize the impact of h_{UAV} (50 m – 400 m) on the received single user data rate considering the space below the UAV and surrounding region. The results are based on analytical modeling of path loss prediction and a set of radio link budget attribute values (select examples presented in Table V and Table VI), varying the UAV altitude.

As can be seen, high-band (24 GHz and 28 GHz) provides the highest rates when the distance between UAV_{gNB} and UE is relatively short, but the rate lowers drastically as the distance between UAV and UE increases over a few hundred meters due to the strong attenuation of this band. As can be expected, the mid-band (3.5 GHz and 6 GHz) performs more constantly at short distances and nearby regions.

Taking a closer look at the short distance (5–200 m) between

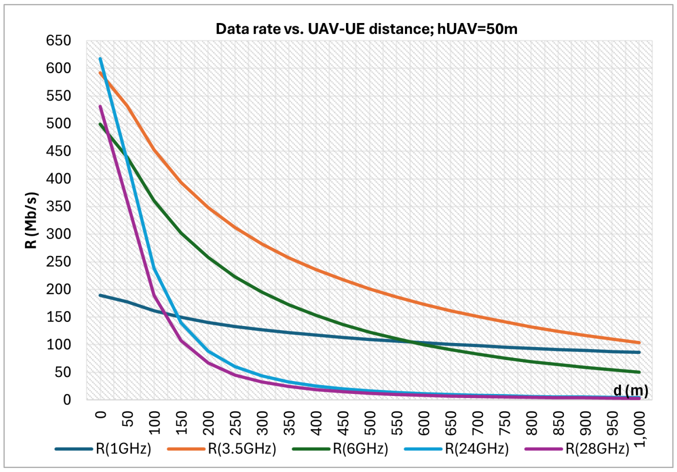

Figure 5. Data rate for UAV-mounted 5G gNB at 50 m altitude

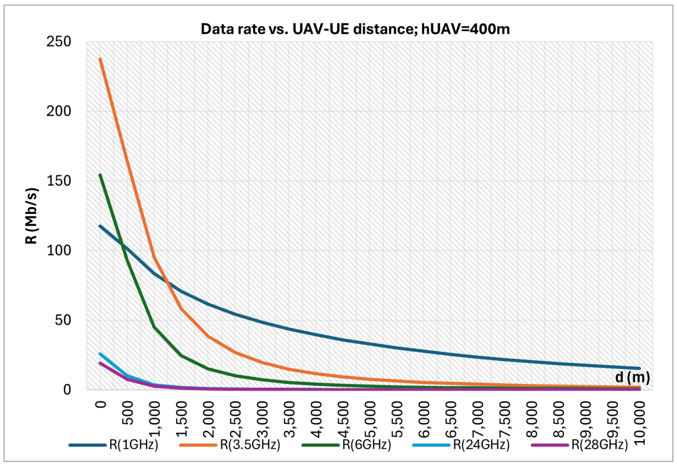

Figure 6. Data rate for UAV-mounted 5G gNB at 400 m altitude

the UAV and UE, Figure 7 shows more detailed behavior. As can be seen, high-band outperforms the other bands up to about 50 m distances providing 1–2 Gb/s data rates, but afterwards, mid-band provides the highest rate (250–500 Mb/s). The heavy attenuation of the high-band makes also the low-band data outperform it beyond 150–200 m distance.

Figure 7 shows that for a critical mission in open and rural areas; if the key requirement is fast data connectivity and high capacity, e.g., for high-definition video contents, high-band provides the most performant service up to about 100 m.

If, instead, the main requirement is a large coverage area (e.g., over 10 km), and the UAV operation is possible at high altitude (e.g., 400 m), low-band is adequate selection as Figure 6 indicates. Should there be limitations for the UAV altitude, such as nearby airports or other restricted areas, mid-band (particularly 3.5 GHz) provides the most adequate balance for h_{UAV} and radio performance, as can be seen in Figure 5.

B. Scenario: IoT

Table VII presents key radio budget items for the IoT scenario comparing NB-IoT class CE0 and CE2, LTE-M, and RedCap.

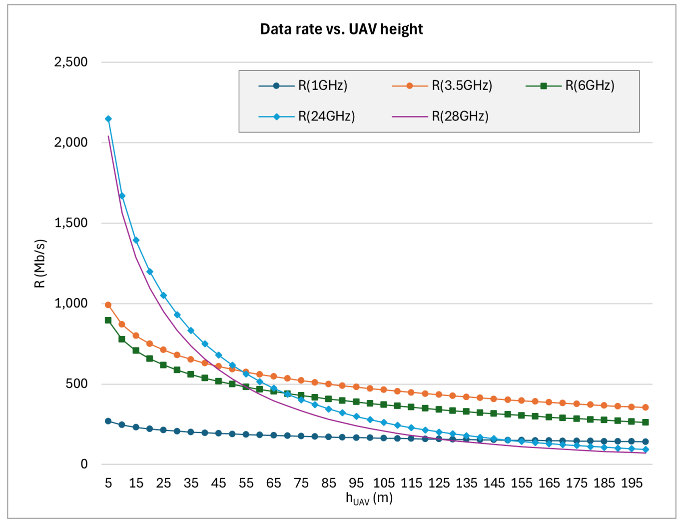

Figure 7. Data rate behavior when the distance between the UAV and UE is short (5-200m)

TABLE VII. APPLIED RADIO LINK BUDGET ITEMS, IOT

Link budget	**NB-IoT$_{CE0}$**	**NB-IoT$_{CE2}$**	**LTE-M**	**Red Cap**
Channel bandwidth, MHz	0.18	0.18	1.40	5.00
Thermal noise floor, dBm	-114.4	-114.4	-105.5	-100.0
Impl. / fade margin, dB	8.0	14.0	8.0	5.0
Required SNR / E_b/N_o	-5.0	-13.0	-7.0	-3.0
RX sensitivity, dBm	-119.4	-127.4	-112.5	-103.0
Peak data rate, b/s	25k	50-100	1M	150M
Path loss budget, dB	**134.4**	**136.4**	**127.5**	**121.0**
Distance (1GHz), km	»35	»35	»35	2̃5
Distance (3.5GHz), km	3̃5	>35	1̃5	7̃

In all these cases, the gNB transmitter power is 23 dBm, TX and RX antenna gains are 0 dBi, and RX noise figure is 7 dB (typical low-cost IoT modem). Again, the free-space path loss model is used in these calculations. Receiver sensitivity is driven by bandwidth, i.e., noise floor plus the required SNR for the lowest modulation / coding of each profile. Path-loss budget is the maximum loss the link can tolerate after allocating the fade / implementation margin. Converting that budget to free-space distance shows the theoretical cell radius; real-world coverage will be smaller due to UAV altitude (earth curvature), foliage, buildings and interference. The presented SNR / (E_b/N_0) values are for the lowest-order modulation / coding in each profile (reference sensitivity) as per the UE RF specifications [27] [28], and the RX sensitivity is N + Required SNR (cross-checked with the specifications for minimum guaranteed UE sensitivity).

As can be seen, NB-IoT can reach the radio horizon even with only 23 dBm EIRP; coverage is limited by geometry, not RF. LTE-M at 1 GHz still covers tens of kilometers, whereas at 3.5 GHz it shrinks to about 15 km LOS. NR RedCap offers the highest data rates but requires roughly 10 dB more SNR than NB-IoT, confining its cell to single-digit-kilometer radii at 3.5 GHz. These tables can be used directly to size UAV altitude, antenna gain, or additional power needed for a given IoT service profile. Compared with the broadband case (for which MCL is 95–105 dB), IoT enjoys tens of dB link budget head-room mainly from the narrow bandwidth and low SNR requirement. Thus, all the presented IoT cases outperform the radio coverage of the eMBB.

VIII. Summary

This study demonstrates that a single-UAV 5G SNPN assembled from COTS components can furnish rapid, standards-based connectivity for both eMBB and IoT use cases in open and rural terrain. Using the ITU-R P.1411 LOS formulation as the baseline propagation model, we quantified how frequency (1–28 GHz) and UAV altitude (50–400 m) shape the coverage–throughput trade-space. The altitude–distance trends and off-nadir penalties are FSPL-driven, with the 100 m footprint ultimately curvature-limited, while mmWave bands deliver the highest short-range rates but degrade fastest with distance. In contrast, mid-band (3.5–6 GHz) offers robust, meter-to-kilometer performance, and low-band (1 GHz) maximizes area at higher altitudes.

Link-budget templates for eMBB and IoT profiles show IoT's tens-of-dB margin advantage from narrow bandwidths and low required SNR, often making coverage geometry-limited instead of RF-limited. Practicality is supported by a lightweight payload bill where the gNB dominates power, informing endurance planning.

Noting regulatory envelopes and spectrum authorization constraints, the results indicate that UAV-based 5G NPN deployment should select band and altitude by required rate vs. area, start with FSPL bounds and subtract environment-specific excess loss, and budget power and weight for the radio. These results provide actionable sizing baselines for future study of multi-UAV extensions and AI-assisted placement.

IX. Future Research

The next step in this study will cover 5G-UAV RAN performance evaluation in expanded terrain types, including low- and high-rise urban topologies, applying up-to-date radio propagation models. The future study also considers extended UAV-based RAN network formation through a drone swarm and will evaluate feasible methods for inter-connected gNBs, including AI-assisted coordination. Future research also considers ways to deploy automated positioning functions for the 5G-UAV network with the underneath UEs for which AI may provide feasible means also in presence of interferences, through advanced sensing techniques.

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