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

The First International Conference on AI-enabled Unmanned Autonomous Vehicles and Internet of Things for Critical Services (AIVTS 2025)

Barcelona, Spain, 26-30 October 2025

Dr. Jyrki T. J. Penttinen
Article author, presenter
Alphacore Inc., Tempe, AZ, USA
jyrki.penttinen@alphacoreinc.com

Presenter

Dr. Jyrki T. J. Penttinen is a Sr. Program Manager at Alphacore Inc., USA. He obtained M.Sc (E.E.) and D.Sc (Tech) degrees at Aalto University (formerly known as Helsinki University of Technology), Finland, on telecommunications, radio technologies, and applied electronics and measurement techniques in 1994 and 2011, respectively. He has worked in telecommunications industry in Finland, Spain, Mexico, and the USA focusing on cellular technologies. His past employers include Telia Sonera, Nokia, G+D Mobile Security Americas, GSMA North America, and Syniverse. He is experienced in research and operational activities including network planning and optimization, measurements, system architectures, and services. Dr. Penttinen is also a lecturer and published author of various books on 5G and other telecommunication technologies.

LinkedIn:	www.linkedin.com/in/jypen
Bio:	www.amazon.com/author/jype
Blog:	www.5g-simplified.com
ORCID:	orcid.org/0000-0002-5097-161X
Alphacore:	www.alphacoreinc.com

Topics of research interest

Dr. Penttinen works at present with Alphacore in Small Business Innovation Research (SBIR) activities. The topics cover advanced integrated circuit blocks and extended wavelength image sensors.

Alphacore researches, develops, and delivers tailored RF or mixed-signal intellectual property (IP), custom macros, and application specific integrated circuits (ASICs). The portfolio include high-performing analogue-to-digital converters (ADCs) and digital-to-analog converters (DACs) for analog, mixed-signal, and RF applications. Alphacore seeks opportunities to team up with interested parties on these topics and beyond.

The interest areas of Dr. Penttinen relate to 5G system and security aspects, network planning, optimization, and deployment, impacts of metaverse on semiconductors, as well as the evolution of cellular-connected uncrewed aerial vehicles (UAVs), Internet of Things (IoT), non-terrestrial networking (NTN), and 6G.

This work

Uncrewed Aerial Vehicles (UAVs) equipped with radios can establish rapid, **ad-hoc connectivity** in areas where terrestrial infrastructure is unavailable or broken.

5G radio access and minimal core functions can be hosted aloft enabling agile IoT or eMBB centric private networks.

This study evaluates the technical feasibility of UAV-mounted **5G Non-Public Network** (NPN) assembled from **commercial off-the-shelf** (COTS) components, comparing the physical radio layer performance of IoT and eMBB use cases.

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.

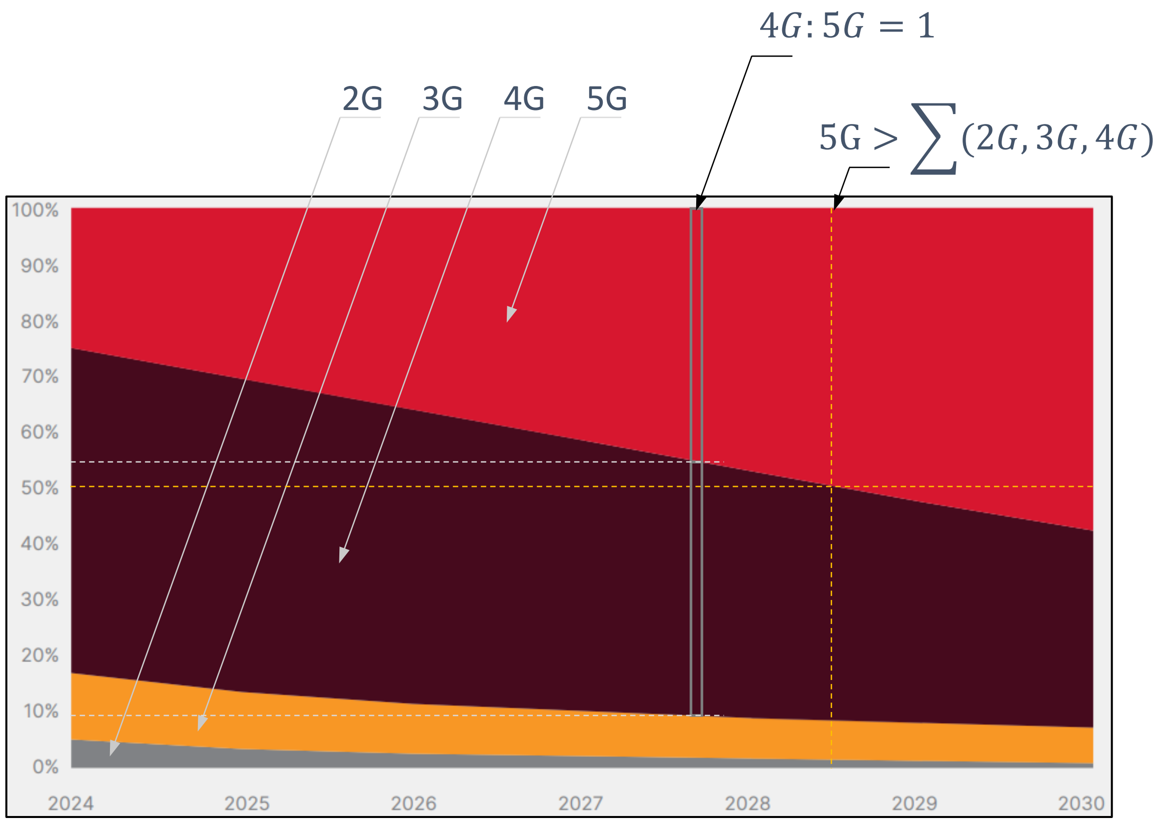
UAV-assisted networking

The GSM Association (GSMA) estimates that the adaption for 5G will surpass that of 4G in 2028.

2G and 3G keep losing their customers, and many of these networks have already been decommissioned.

6G will be reality around 2030 through the first technical specifications of 3GPP aligned with the ITU IMT-2030 performance requirements.

Meanwhile, 5G is the most performant mobile communications system in 2020s, and it is becoming suitable for also UAVs that can be cellular-connected or form part of network[1].



Mobile adoption by technology: percentage of total connections[2]

[1] *Cellular-enabled Aerial Vehicles: https://www.gsma.com/about-us/regions/north-america/wp-content/uploads/2023/12/GSMA-North-America-Drones-White-Paper_Final-Nov_30_2023.pdf*

[2] *Image source: GSMA Mobile Economy Report 2025 (www.gsma.com/solutions-and-impact/connectivity-for-good/mobile-economy/wp-content/uploads/2025/04/030325-The-Mobile-Economy-2025.pdf)*

State of the Art: UAVs as a network element

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 and how to enable group handover for drone base stations.

An example of current UAV-based networking is AT&T's 5G Cell on Wings (CoW), a drone-mounted cellular 4G or 5G base station that temporarily extends the respective radio coverage to improve network performance and provide connectivity, e.g., during disasters and large events.

Nevertheless, the available studies are not necessarily conclusive in terms of the:

- **tradeoffs of the UAV altitude,**
- **deployed frequency bands,**
- **select radio link budget parameters** in varying geographical topologies, and
- **realities of concrete COTS components**.

Furthermore, the adaptation of **optimal architectural models of UAV-networking** for isolated cases can benefit from further studies.

Novelty

This research:

1. Presents a concept based on 3GPP-defined **non-public network (NPN) architecture** and available **COTS** components to provide **aerial IoT and data services** to a variety of use cases.
2. Evaluates the **performance** of such a solution comparing UAV-mounted 5G gNB coverage and capacity of eMBB and mMTC.

This initial design considers a single UAV that provides local communication to the UEs underneath.

The study paves the way for the forthcoming work that will investigate:

- formation of a multi-UAV-based 5G RAN service and
- automized location functions through advanced sensing and artificial intelligence.

IoT vs. eMBB

eMBB provides very high data rates.

IoT, through several variants, provides robust connectivity for low or medium speed data.

Link budget term	eMBB	IoT
Channel bandwidth B	20 – 400 MHz	180 kHz – 20 MHz
SNR (BLER<10%)	8 – 15 dB (64 / 256 QAM)	-13 – -3 dB (BPSK / QPSK, heavy coding, repetitions)
Fade/penetr. margin	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

IoT relies on robust modulation schemes and HARQ (Hybrid Automatic Repeat reQuest) repetition balancing throughput and coverage.

Also, 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), and IoT sensors may be often in basements and metal cabinets increasing fading margin.

Aerial NPN considerations

3GPP facilitates private network realizations through standalone non-public network (**SNPN**) and public network integrated non-public network (**PNI-NPN**)[3].

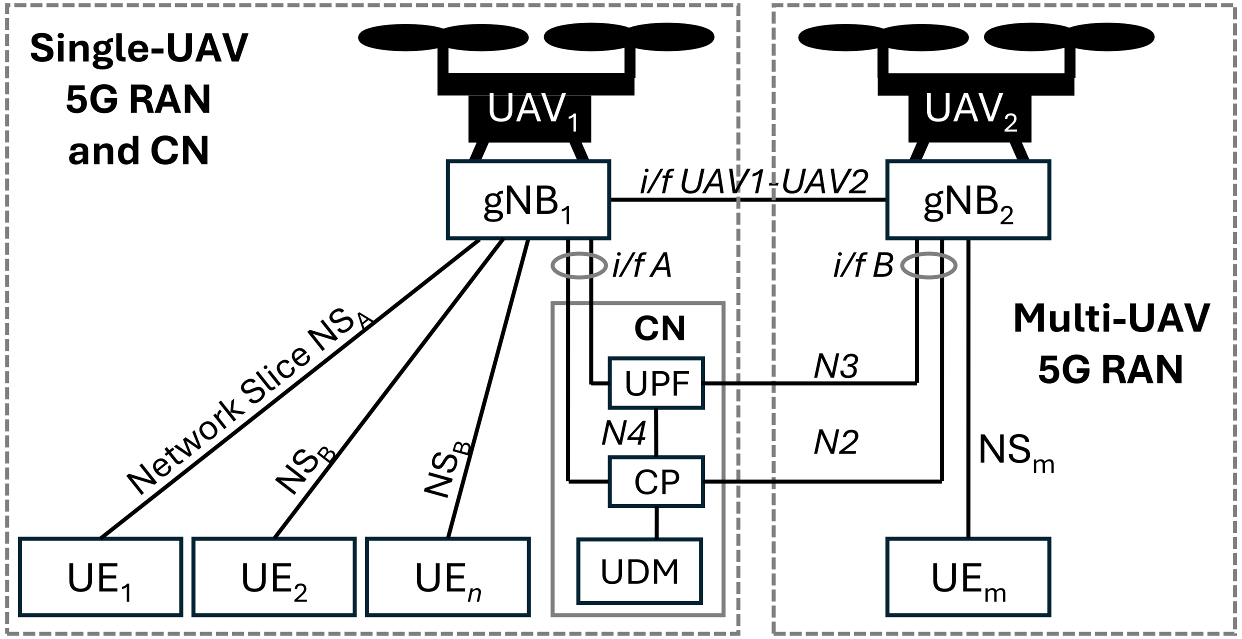
Variant	Assessment
SNPN (fully standalone)	Best for autonomous, localized, quick-to-deploy networks (no MNO dependency)
PNI-NPN with RAN sharing	Enables UAVs to share ground RAN where available, while maintaining separate core
PNI-NPN with core sharing	UAV-based NPN reuses public 5G core network, allowing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

Although 3GPP designed these models for terrestrial networking, their principles can be extended to serve also in aerial networks.

SNPN is self-contained and independently operated from public networks. It is adequate for rapid deployment for on-demand aerial networks with no dependency on commercial MNO infrastructure.

[3] For information on 5G NPN variants, see J. Penttinen et al "**On Techno-Economic Optimization of Non-Public Networks for Industrial 5G Applications**," The Nineteenth Advanced International Conference on Telecommunications AICT 2023 (https://www.iaria.org/conferences2023/filesAICT23/AICT_10003.pdf)

5G-capable UAV realization



The system considered in this study is based on minimal viable 5G SNPN architecture and a single UAV equipped with a 5G gNB enabling local connectivity to the UEs underneath.

This Figure presents the UAV-based SNPN realization.

A set of UAVs house radio functions of gNBs, whereas the essential core network (CN) network functions (NFs) can be physically located 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 PC5 link) forming a 5G RAN drone swarm.

Equipment considerations

To deploy a 5G SNPN UAV radio service, the UAV can host a basic integrated gNB (e.g., Amarisoft / Parallel Wireless).

The basic location management is assumed to be manual and GPS-assisted, but automated methods can also be developed based on UE signals and using basic RF heuristics to position the UAV(s) according to user density.

Basing the solution on commercial off-the-shelf (COTS) devices, this Table presents a set of candidate elements for a simplified functional architecture.

Layer	Function	Realization
Radio Access	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	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 (5G Sidelink)

Equipment considerations

This Table 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, the total UAV payload (essential RAN components) is approximately 2.5–3.0 kg, which is feasible for medium-class UAVs (e.g., DJI Matrice 300 RTK or similar custom UAVs).

The most challenging item payload-wise

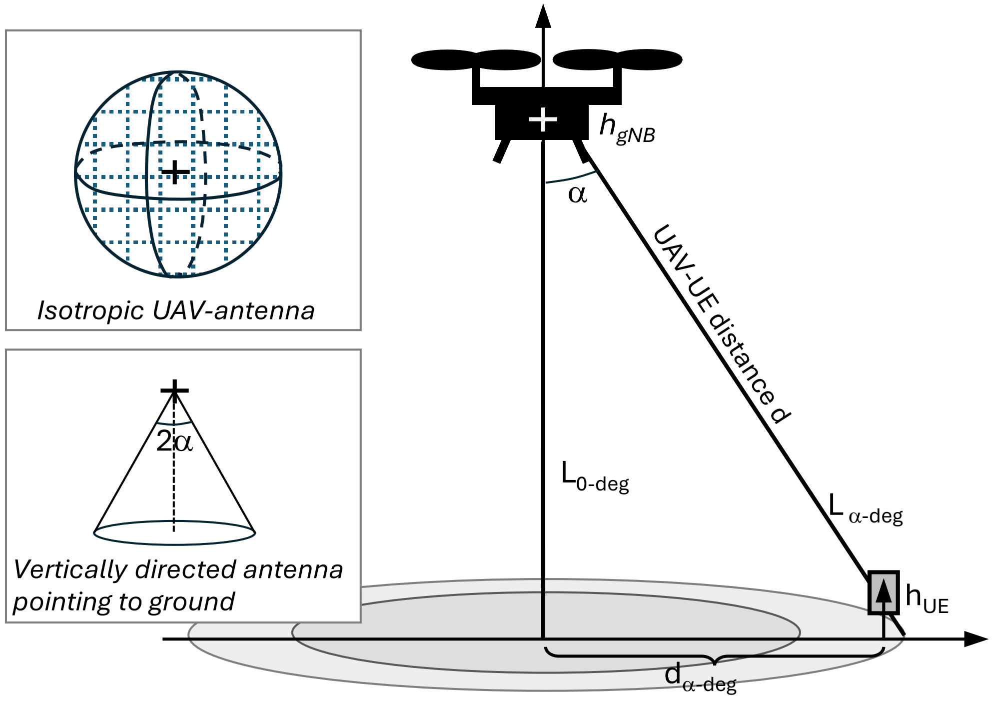
Component	Description	Example	Weight
Integrated 5G Small Cell	Embedded gNB; RU (SA mode)	Amarisoft Callbox Mini / Baicells Nova430	400–800g
Lightweight Compute Module	For basic UAV / swarm logic	Raspberry Pi CM4 or Jetson Nano	100–200g
Simple Mesh Swarm Radio	IEEE 802.11s Wi-Fi 6 / V2V PC5	Compex WLE900VX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

Physical radio interface

Goal: find optimal coverage, quality, and performance as a function of single UAV altitude in rural and open areas

- f = low (1 GHz), mid (3.5/6 GHz), high (24/28 GHz);
- UAV altitude h_{gNB} = 50m, 100m,..., 400m
- UE type = pedestrian;
- Power = P_{UE} +23 dBm, P_{gNB} +23 dBm;
- UAV antenna type = omni-directional (0 dBi)

The key results: cell size and respective data rate estimate for both eMBB and IoT use cases.



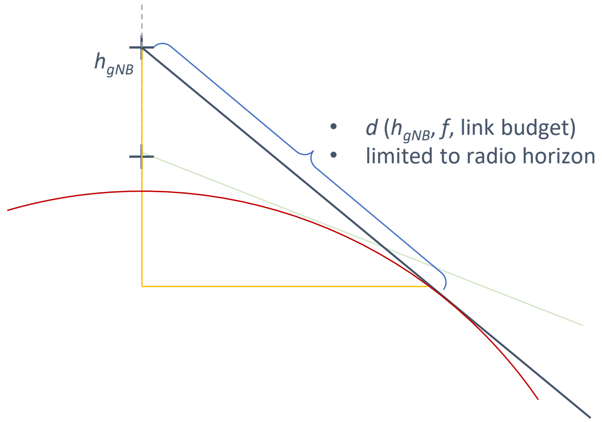
$$L_{FSPL} = 20\log_{10} f + 20\log_{10} d + 92.45$$

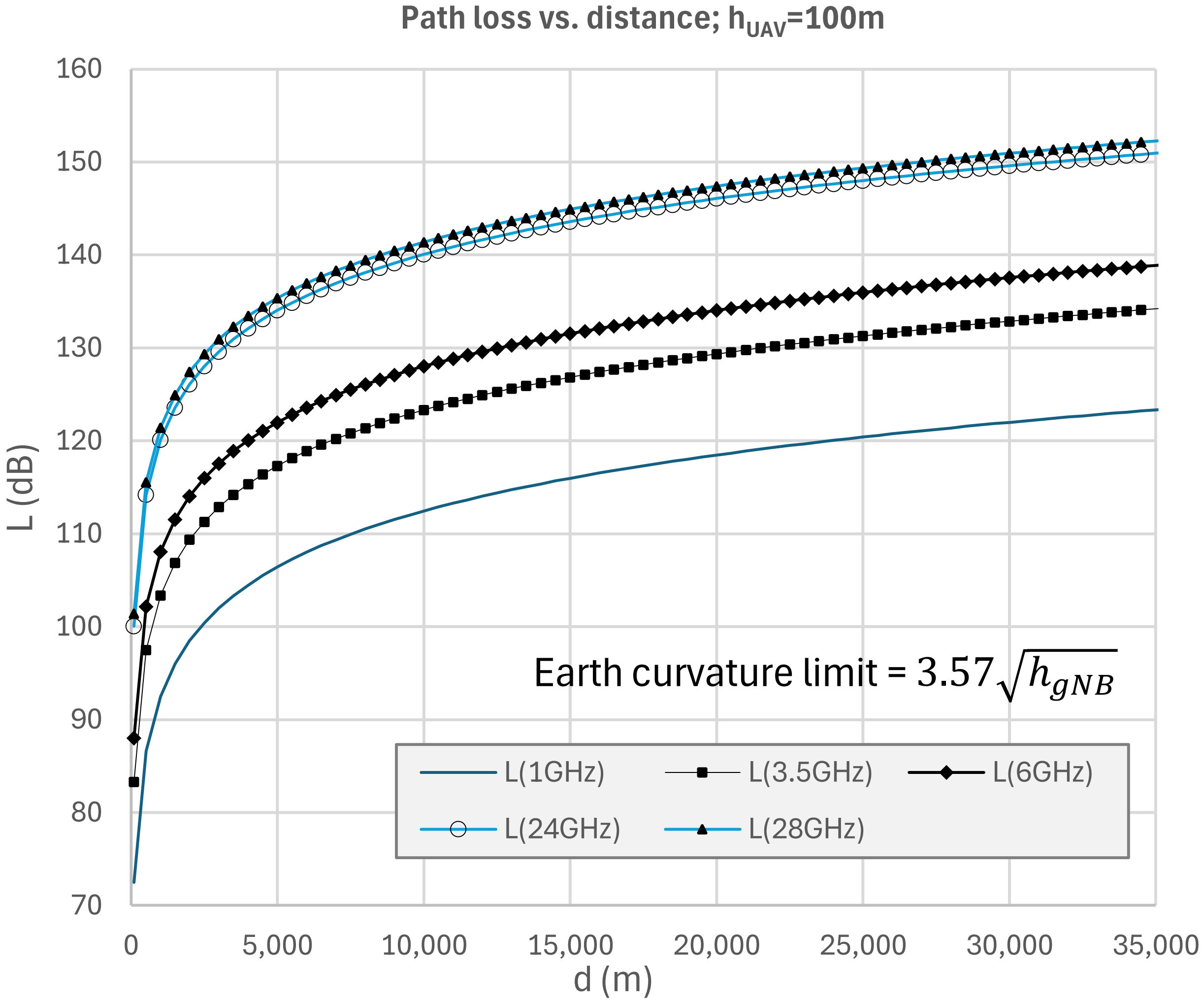
(f in GHz, d in km)

ITU-R P.525 model (within version 12 of ITU-R P.1411)

Radio interface considerations (1 of 2)

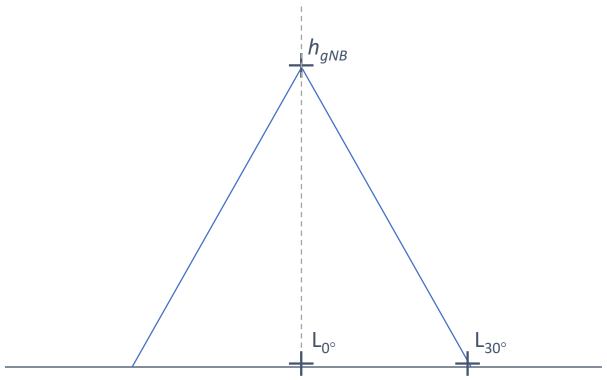
Applying ITU-R P.1411, this Figure presents an example of the path loss UE-UAV at a distance d from UAV's location for isotropic UAV TX antenna at 100m altitude (earth curvature limit is about 35 km in this case).

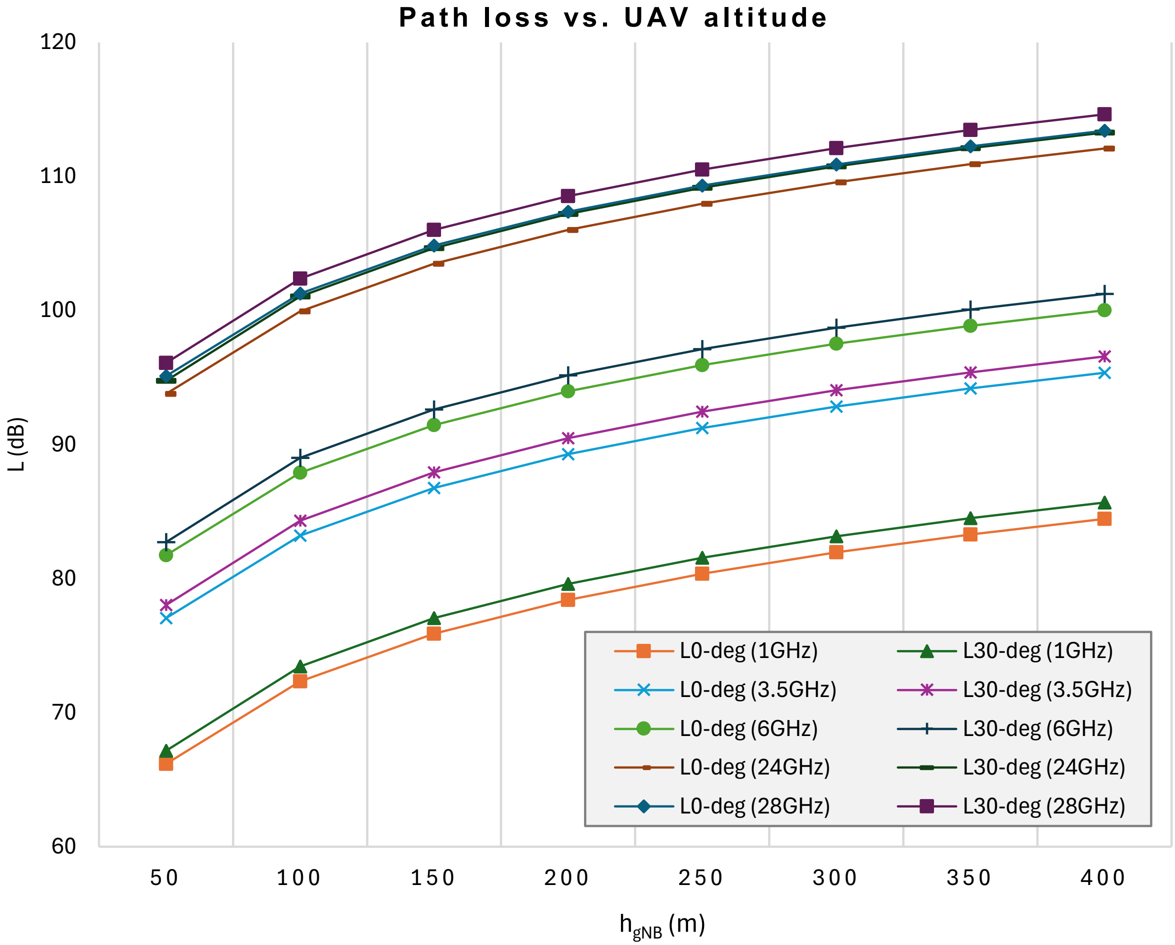




Radio interface considerations (2 of 2)

This Figure summarizes the estimated path loss values L (dB) directly beneath (α=0°) and off the vertical location of the UAV (α=30°) in open and rural areas varying the altitude of the UAV.





Scenario: eMBB

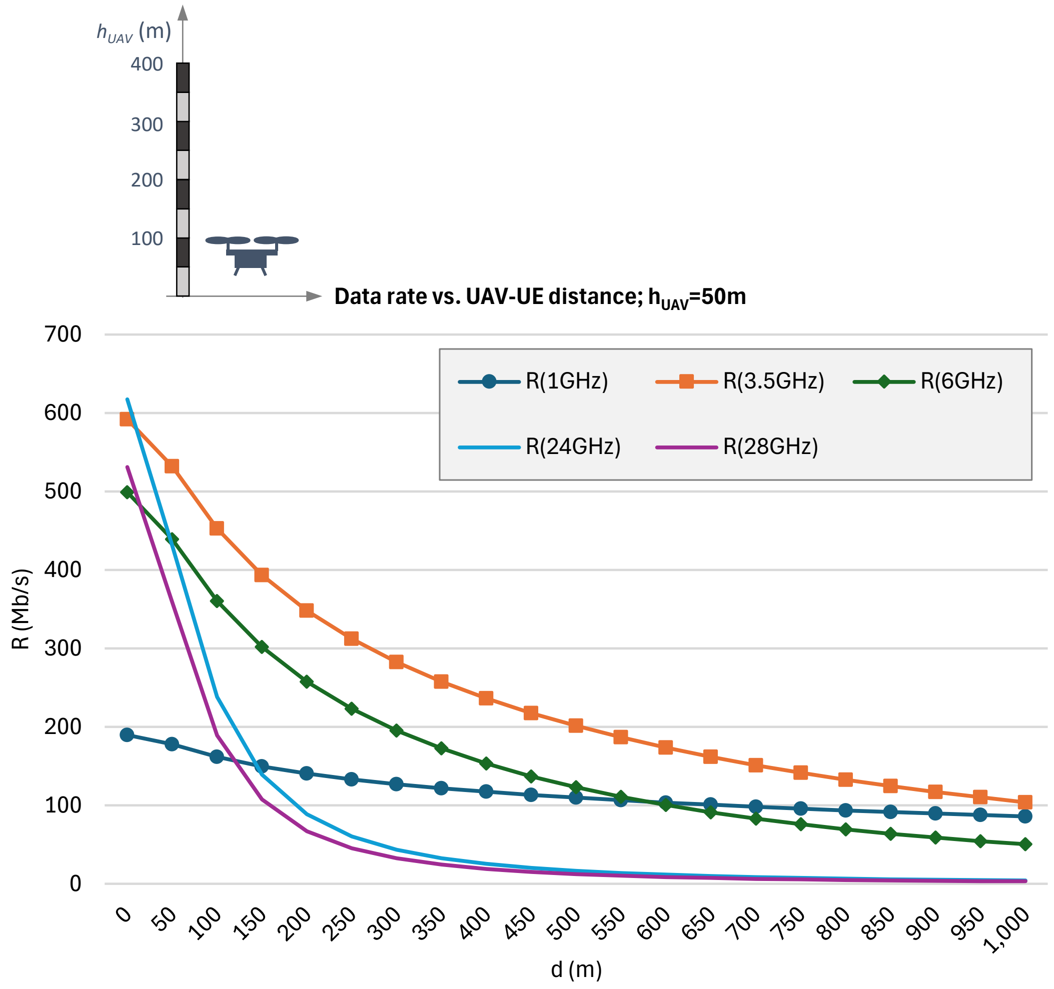
These Tables present the key eMBB radio budget items, and an example of the radio link budget values when the UAV altitude is 400 m and the UE is located underneath.

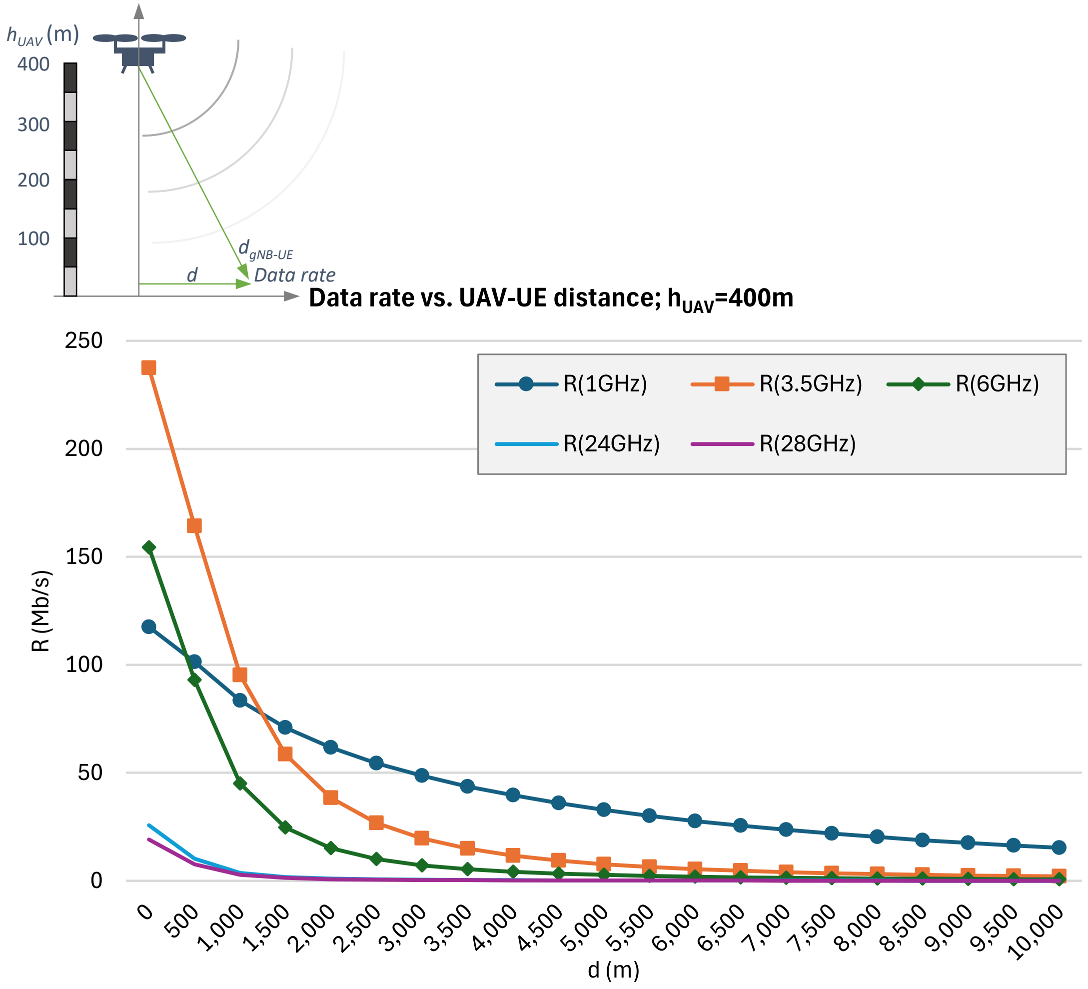
Spectral efficiency η(bps/Hz) = $0.6 \cdot \log_2(1+\mathrm{SNR})$
Received power $P_{RX} = P_{TX} + G_{TX} + G_{RX} - L$
Noise floor $N = -174 + 10 \log_{10} B + NF$
SNR after margin = $P_{RX} - N - M$
Spectral efficiency $SE = 0.6 \cdot \log_2(1+10^{\mathrm{SNR}/10})$
Data rate $R = SE \times B$

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	$N_o = kT = 1.38 \cdot 10^{-23}$ J/K · 290K

Link budget, h_{UAV}=400m, α=0°	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	-174.0	-174.0	-174.0	-174.0	-174.0
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

Results: eMBB





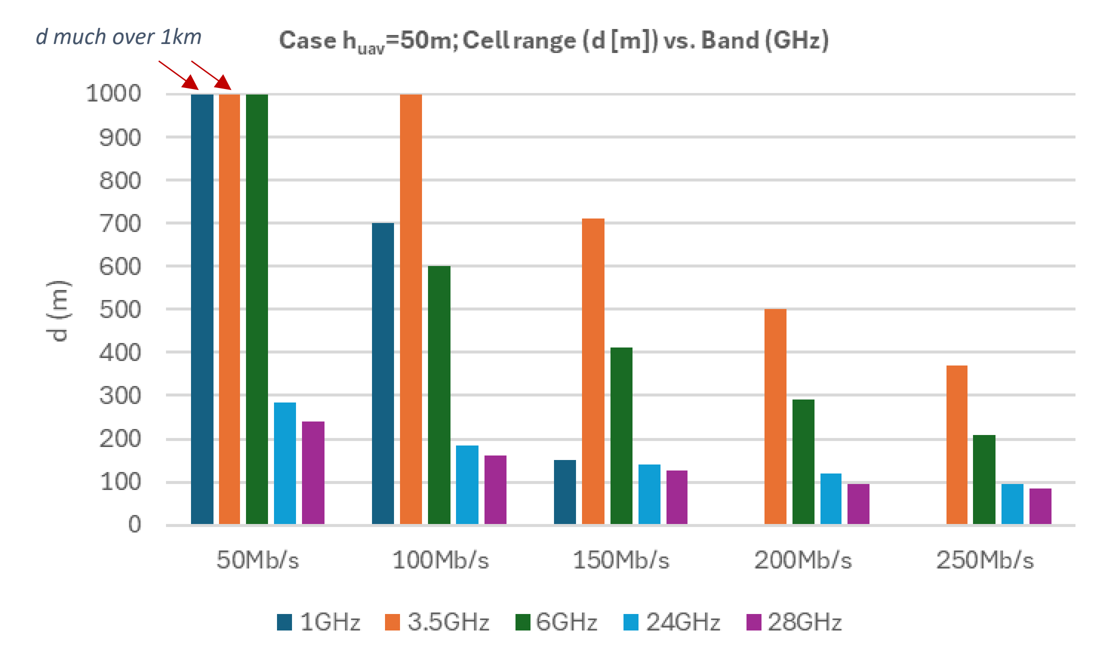
Cell range

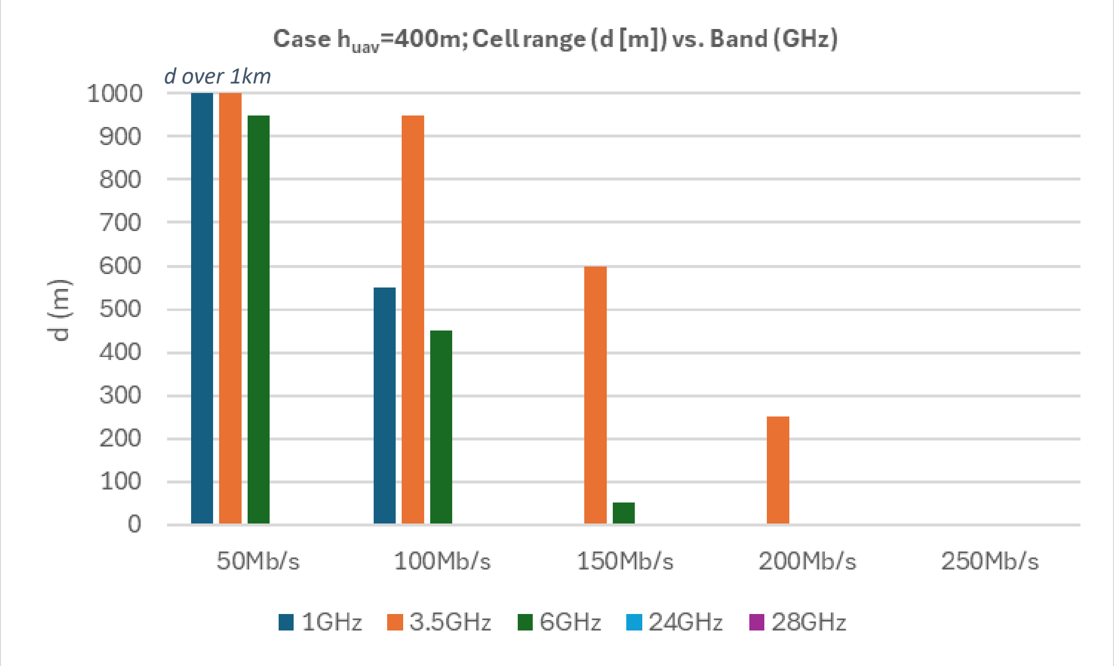
When UAV altitude is 50m:

- High band data is lower compared to the nearest comms
- Mid-band data provides good performance
- Low-band provides steadily good coverage for decent rates

When UAV altitude increases 50m → 400m:

- High band data becomes practically obsolete
- Mid-band data provides optimal performance
- Low-band provides steadily good coverage for low bit rates





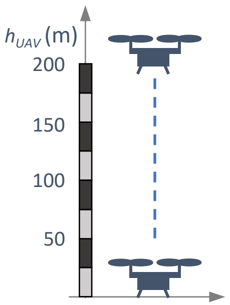
eMBB service at very low UAV altitudes

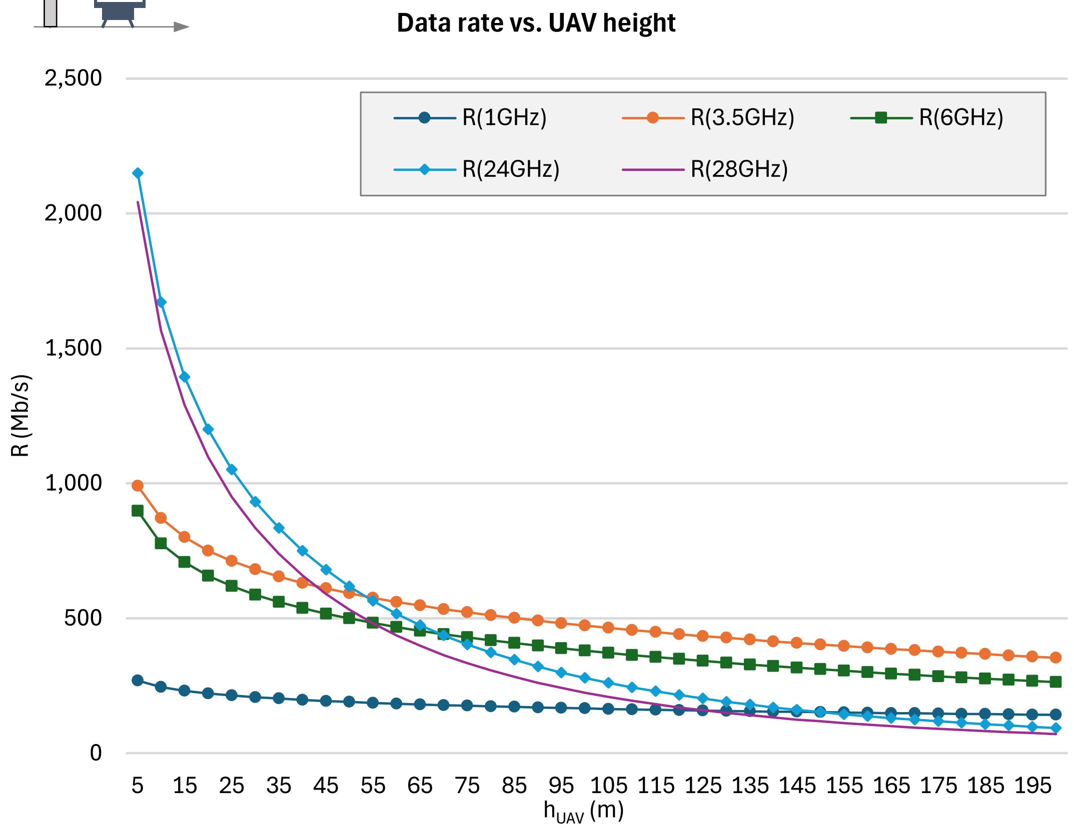
High-band provides the highest rates when the distance between UAV_{gNB} and UE is relatively short, but the rate lowers drastically as the distance between UAV and UE increases over a few hundred meters due to the strong attenuation of this band.

Mid-band performs more constantly at short distances.

High-band outperforms the other bands up to about 50 m distances providing 500 Mb/s–2 Gb/s data rates, but afterwards, mid-band provides the highest rate (250-500 Mb/s).

The heavy attenuation of high-band makes the low-band data outperform it beyond 150–200 m distance.





Scenario: IoT

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

In these scenarios, the gNB P_{TX} is 23 dBm, TX and RX antenna gains are 0 dBi, and RX noise figure is 7 dB (typical low-cost IoT modem).

The presented SNR / (Eb/N_0) values are for the lowest-order modulation / coding in each profile (reference sensitivity) as per the UE RF specifications, and the RX sensitivity is N + Required SNR (cross-checked with the specifications for minimum guaranteed UE sensitivity from the 3GPP specifications).

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	~25
Distance (3.5GHz), km	~35	>35	~15	~7

Results: IoT

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 case.

Summary

This feasibility study focuses on a single UAV-mounted 5G gNB that provides isolated wireless coverage in open and rural areas and serves as a complementing communications method for underlying UEs.

The study shows that a COTS-based realization for deploying a UAV-based gNB is feasible selecting a drone that supports the required payload, the power management being .

The cost of drone and COTS-based 5G components, e.g., relying on Open RAN, can be adequate compared to the benefits such as solution provides over terrestrial trailer-mounted setup.

The results show that

- in aerial eMBB scenarios, the 5G frequency band selection plays a key role, so it is important to evaluate the requirements and respective tradeoffs of bands, expected UAV altitudes, and required capacity and data rate figures;
- low or moderate bit rate aerial IoT service can be realized for very large areas basing on feasible drone and radio link budget parameter values.

For further information, please do not hesitate to contact:

Jyrki T. J. Penttinen

jyrki.penttinen@alphacoreinc.com

www.linkedin.com/in/jypen

I gratefully acknowledge the feedback of Professors M. Reisslein, G. Trichopoulos, S. Zeinolabedinzadeh, and A. Alkhateeb of Arizona State University on this work.