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An enhanced design of a 5G MIMO antenna for fixed wireless aerial access

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Abstract
A recent market prediction is that 5G Fixed Wireless Access (FWA) will more than double over the next five years and trials at the same period in London suggest promising results. However, the shift to 5G FWA has raised a new set of research challenges in relation to speed of deployment and re-deployment, coverage, power consumption, end user mobility and last mile connectivity, to name just a few, because of the much higher expectations. A recent review reveals that key 5G Physical Layer technologies that will enable wide mobile and FWA have not kept up pace. In response to some of those research challenges, this paper presents the design of a 5G Multiple Input Multiple Output (MIMO) Antenna that is mounted on a tethered aerostat, and the combination of which serves as a 5G FWA aerial station. The antenna design features several novelties and the aerial station can provide last mile connectivity to a wide coverage footprint, with moderate power consumption and operating at high speeds. Both the evaluation of the antenna performance using several key performance indicators and the validation of the aerial station as a 5G FWA in a wireless sensor network (WSN) proof-of-concept application reveal efficiency gains.

Keywords 5G MIMO antenna · Tethered aerial aerostat · Fixed wireless access

1 Introduction

A market analysis report which appeared at the end of 2020 suggests that 5G FWA will grow by 136% by 2026 [1]. A report by ITU which appeared at the same time argues that 5G FWA trials conducted in London utilizing Samsung's 5G network using the 28 GHz mmWave spectrum offers promising results [2]. However, a review by Morais also in 2020 [3] on Key 5G Physical Layer Technologies Enabling Mobile and FWA concludes that there is little to date in literature on 5G FWA.

Furthermore, the pandemic has exacerbated the fallout from poor or lack of connectivity when access to education, healthcare, business, and important information was only through the Internet as working, studying, and doing business from home became the new normal. However, this has opened up to a plentitude of new fixed wireless aerial solutions which include novel combinations of Unmanned Aerial Vehicles (UAV), Robotics, Artificial intelligent (AI), Biotechnology, Internet of Everything (IoE) to name just a few as Fig. 1 shows as these offer significant advantages over terrestrial systems, i.e. wider coverage footprint, deployment flexibility, terminal mobility and importantly guaranteed last-mile connectivity [4–8].

Aerial Platforms including tethered aerostats are regularly used as atmospheric layer repeaters sited at an altitude between 1 and 20 km above ground [9]. These helium-filled and solar-powered platforms have been re-deployed with various applications such as broadcasting, surveillance, navigation, and much more. Tethered aerostats capitalize on the strengths of terrestrial and satellite communication systems and exhibit none of their weaknesses.

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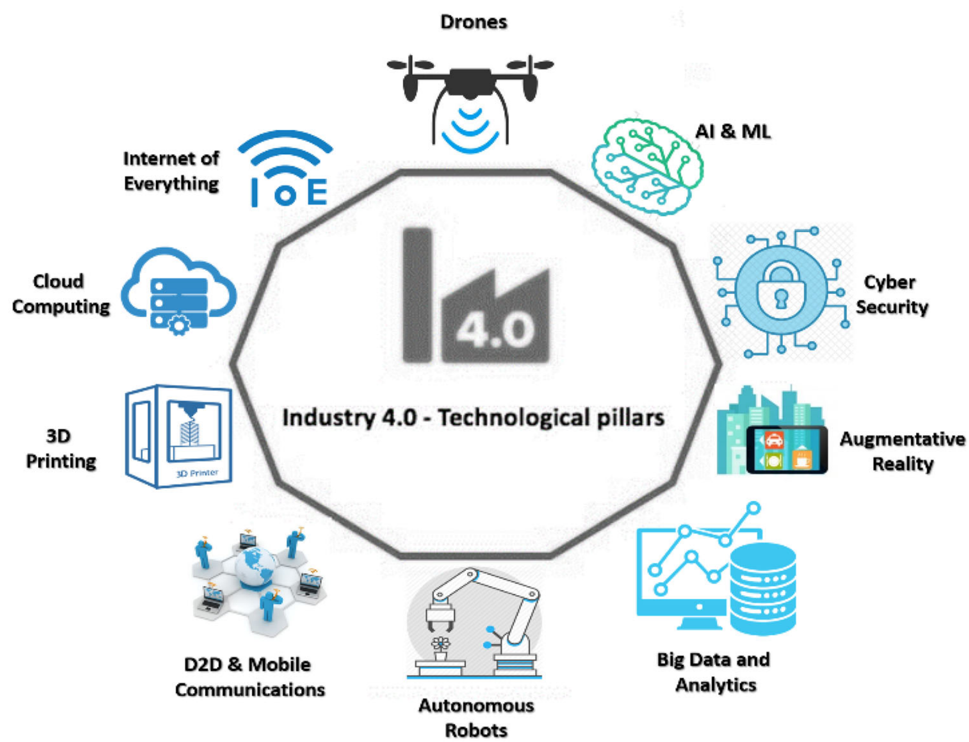

Fig. 1 Industry 4.0 technological pillars [68]

The recent shift from mainstream approaches to 5G FWA has raised a new set of research challenges, the result of much higher expectations with speed of deployment, coverage, power consumption, end user mobility and last mile connectivity among other. This paper aims at designing a 5G MIMO Antenna that is mounted on a tethered aerostat, and the combination of which serves as a model of a 5G FWA aerial station that resolves a few research challenges.

The rest of this paper is organized as follows: Section II presents related research work in support of the design; section III describes the Model of a 5G Wireless Fixed Aerial Access Station that results from the design and mounting of the 5G MIMO antenna on a tethered aerostat; section IV evaluates the design of the model and in particular the antenna; section V validates the model through proof-of-concept applications in an existing WSN; section VI concludes.

2 Related Research Review

The focus of the related research review is a set of issues that affect the performance of FWA when using a 5G MIMO antenna to provide last mile connectivity especially from aerial stations. All works published within the last year unsurprisingly conclude that 5G FWA is in its early infancy unlike pre-5G FWA and go on to highlight a few research gaps to move the 5G FWA agenda forward. 5G FWA, unlike its predecessors, is scarcely reported in literature, let alone onboard an aerial platform serving as an aerial access station for providing last mile connectivity that comes with its own challenges when setting up for last mile connectivity.

5G FWA is regarded as a more cost-effective approach to providing rapid last mile connectivity rather than leased lines and/or fibers. The combination of 5G technology over a standardized 3rd Generation Partnership Project (3GPP) architecture enables operators to deliver high speed broadband services in the high spectrum of 28 GHz to 39 GHz and meet the exponential demand as reported by Ericsson and Nokia Bell Labs [3, 10, 11]. This seems to work reasonably well in suburban areas with MIMO antennas mounted on base stations at an altitude of 6-8 m and operating at a frequency of 28 GHz. Key performance indicators include throughput, coverage, and antenna radiation. [10] reports on a field FWA experiment in which the performance of a massive MIMO is assessed in relation to throughput.

[12] argues that the issue of providing cost-effective high-capacity transport for FWA deployments remains an open challenge and propose in response an optical transport for 5G FWA networks to minimize the deployment cost and meet network requirements. Early-stage experiment results in eastern suburban Australia confirm that the optical x-haul of a 5G FWA network is a vital future-proof FWA deployment. [13] presents the performance assessment of a 5G Radio Access network at an altitude of 35 m

for both stationary and mobile users alike in relation to throughput and probability of blocking. Results indicate high capacity and wide coverage area.

[14] considers beamforming with massive MIMO for achieving wide footprint coverage, control channels and with moderate power consumption. [15] stresses on the importance of MIMO beamforming for an angular spread in suburban radio channels and assess performance in relation to a Cumulative Distribution Function (CDF), path loss, Signal to Interference Noise Ratio (SINR), and antenna gains with different antenna patterns. They report upto 60% cell edge capacity improvements.

[16] assesses the performance of a 5G FWA case study using transmission and throughput as performance indicators. [17] reports on the experimental use of MIMO for 5G FWA in support of smart indoors and outdoors city applications. The results of measuring path loss, received power, SNR and antenna delay spread indicate a performance improvement with a shift from urban to suburban as shadowing decreases and Line of Sight (LoS) connectivity increases, especially if transmitter altitude increases.

[18] considers alternative 5G FWA rural deployments with varying spectrum, infrastructure, region, and mobility and concludes that 5G FWA is the most suitable choice for last mile in sparsely populated. [19] discusses the link budget requirements of 5G FWA and highlights an example of suburban deployment using MIMO beamforming. Performance is assessed through path loss, CDF of Effective Isotropic Radiated Power (EIRP), throughput, received power, and radiation power of arrays. Connectivity and coverage footprint may be improved through optimization of the propagation model.

[20] uses path loss and average transmission rates to carry out performance analysis of scalable 5G FWA solutions with antenna diversity techniques. The results indicate that a 5G MIMO antenna would considerably improve performance. [21] evaluate the design of 5G MIMO antenna using the antenna gain, radiation efficiency and antenna resonance frequency inside the cavity.

Research trials worldwide strive towards providing wireless connectivity via aerial platforms at different altitudes using different communication standers and antenna types, for example, Microwave Access (WiMAX), Long-Term Evolution-Advanced (LTE-A), Industrial, Scientific and Medical (ISM), or wireless fidelity (Wi-Fi) [22–24]. Aerial platforms including tethered aerostats act as satellites with regards to altitude, footprint, deployment flexibility, terminal mobility, and last mile connectivity but without the distance penalty. However, [25, 26] argue that altitude plays an important role since the payload weight and power consumption may affect the performance. [23, 27–29] draw a direct line between maximizing footprint coverage with altitude where pressure, wind speed, temperature, transmission power, and different antenna configuration need to be considered. [30, 31] argue that a high aerial altitude would give a wider footprint coverage with increased LoS connectivity and yet it may yield less throughput with high path loss and power consumption. Therefore, there is a need for a trade-off and some degree of optimization to improve performance.

[32] propose the idea of delivering internet connectivity to rural areas using tethered aerostats with Wi-Fi (802.11a, b, g) wireless point to multipoint. Aerial platforms tend to utilize MIMO antennas due to their potential of diversity gains which in turn may lead to maximizing capacity and link budget, extending coverage range, improving Quality of Service (QoS), reducing battery requirements and minimizing power transmission and fading [22, 25, 33–39]. [40] argues that improved reliability, wireless connectivity, and energy efficiency may be maintained by using beamforming via MIMO techniques.

[41] experiments with a tethered-blimp balloon at a 400 m altitude whose purpose is to provide Emergency Broadband Access Network (EBAN) access for relief operations in Indonesia. It uses an ATG model and both WiFi and WiMAX technology. Signal Level (RSL) and Signal-to-Noise Ratio (SNR) are used in assessing performance. Google Loons is a growing aerial platform technology for providing high-speed cost-effective Internet for commercial usage [42] and low altitude aerial platforms powered by batteries or solar panels are now being widely used to provide Internet access during special events, in rural zones, and in the immediate aftermath of disasters [43]. [44] investigates the challenges arising from the use of WiMAX, WiFi, LTE, ZigBee, and XBee technologies on aerial drone platforms in remote and hostile environments for emergency, and search and rescue operations and concludes that coverage and throughput is not served well by omnidirectional antennas.

Power consumption at the receiver side has been discussed broadly from a WSN performance prospective [45, 46]. Many methods have been tried at improving QoS results, which in turn enhance power consumption. The authors in [47–50] have considered various techniques to serve the purpose of improving power consumption while transmission link and connectivity have been kept at a reasonably good-level. Examples of such techniques include minimizing path loss which may lead to improved RSS, power scheduling schemes, modulation selection, finding an optimum target BER probability and packet length, and Collaborative Beamforming.

Wireless connectivity can be attained via a propagation model which comes in two types for aerial platforms: Free space models such as Two-Rays and Air-to-Ground [22, 51–53] which relay on a closed-form formula that includes both Line-of-Sight (LoS) and Non-Line-of-Sight

Table 1 Summative review of recent and current research

Ref	Issues addressed							Issues Unresolved
	Base type	Frequency band	Objective	Propagation model	Tx altitude	Antenna type	FWA	
[3]	Terrestrial	28 GHz	High-speed Internet	Statistical	6 m	8 × 8 MIMO	√	Limited capacity due to transmitter altitude
[10]	Terrestrial	3.5 GHz	Field trial	Free Space	NA	2 × 2 MIMO	√	Low performance due to low MIMO capacity
[12]	Terrestrial	NA	High-speed internet	Free space	NA	Omni-directional	√	Limited capacity due to antenna type
[13]	Terrestrial	3.6 GHz	Internet access for stationary and mobile	Rural microcell	35 m	MIMO	√	Limited capacity due to low frequency
[15]	Terrestrial	28 GHz	Internet access in suburban zones	Statistical	8 m	8 × 8 MIMO	√	Optimized antenna pattern does not align for wide coverage through higher altitude
[17]	Terrestrial	60 GHz	Internet access for indoors and outdoors	2-Ray ground reflection	15 m	MIMO	√	Limited capacity due to antenna type and transmitter altitude
[19]	Terrestrial	39 GHz	Internet access in suburban zones	Large-scale channel	25 m	MIMO	√	Limited capacity due to transmitter altitude and propagation model
[20]	Terrestrial	10 GHz	Simulation test	Stanford University Interim (SUI)	30 m	MIMO	√	Antenna type
[51]	High altitude platform	2.5 GHz (Mobile WiMAX)	Internet for emergencies	ATG	5 km	MIMO	–	Limited capacity due to low frequency
[53]	Low altitude platform	3.5 GHz (WiMAX)	Internet for emergencies	Okumura	1 km	MIMO	–	Low performance due to low transmission power
[53]	High altitude Platform	3.5 GHz (WiMAX)	Internet for emergencies	ATG	20 km	MIMO	-	Limited capacity due to huge altitude
[54]	Tethered balloon	1.5 GHz (3G)	Internet access	Hata	200 m	Omni-directional	–	Limited capacity due to antenna type and frequency
[55]	Low Altitude platform	3.5 GHz (WiMAX)	Internet	Okumura	400 m	MIMO	–	Large installation and operational costs
[56]	Tethered balloon	1.7 GHz (4G)	Internet for emergencies	Free Space	440 m	Omni-directional	–	Limited capacity due to antenna type and frequency
[32]	Tethered aerostat	2.4 GHz (WiFi)	Internet access in rural zones	Free space	10 km	Omni-directional	–	Limited capacity due to antenna type and frequency
[41]	Tethered blimp	2.4 GHz (WiFi)	Internet for emergencies	Free space	400 m	Directional	–	Limited coverage due to antenna type and low transmission power
[42]	Google balloon	2.4/5.8 GHz (LTE)	Internet in remote zones	Free space	20 km	3G antenna	-	Limited capacity due to altitude and antenna type
[43]	Tethered balloon	0.9–6 GHz (3G, LTE, WiMAX)	Internet for emergencies	Free space	25 m	Directional helical	–	Limited capacity due to altitude and antenna type
[44]	Drone	5.85 GHz (WiMAX)	Rescue missions	Free Space	500 m	Omni-directional	–	Large installation and operational costs
[47]	UAV	3.5 GHz (WiMAX)	WSN	Empirical	1 km	Omni-directional	–	Limited range and large operational costs
Own proposal	Tethered aerostat	28 GHz	Internet access in suburban zones	Optimized model	1 km	5G MIMO with adaptive beamforming	√	–

(NLoS) conditions, as well as an elevation angle consideration; empirical propagation models such as Ericson and Okumura [40, 54–57] which relay on a pre-defined set of constants and constraints for different geomorphologies. Both types of models offer advantages and disadvantages in relation to the performance of any propagation model.

Table 1 presents the research gaps identified through a summative review of recent and current research on last mile connectivity using 5G FWA. After careful consideration of these research gaps, we draw our own research motivations to inform our own proposal which conclude this section.

Our summative review on Table 1 reports on the sparse use of 5G MIMO antenna for FWA, especially onboard aerial platforms that serve as aerial access stations for providing last mile connectivity as well as several design limitations. Our proposal to mount a 5G MIMO antenna onboard a tethered aerial aerostat is not just a practical solution to serve emerging needs for last mile connectivity on the go but features several design novelties as follows:

- A massive 8 × 8 MIMO antenna with a planar phased array of 64 patches designed for operation at 28 GHz.
- The patch geometry that uses the optimum feed location to produce an optimal return loss as this impacts the resonant frequency and input impedance.
- The phasing at each patch is adjusted to create beams that sweep in a single plane, with all patches performing adaptive beamforming with the inclusion of spatial multiplexing that improves data rates and reduces interference.
- The positioning of the massive 8 × 8 MIMO antenna is steered so that by using the elevation angle (θ) to optimize a free-space path loss model when propagating signals from the tethered aerostat to terrestrial users using a LoS connectivity, leads to improved reliability and reduced power consumption.

The proposed prototype aims at shifting away from past and mainstream approaches and capitalizing on the benefits of fast deployment and re-deployment on the go, which come with the promise of wider coverage, moderate power consumption, end-user mobility and guaranteed last mile connectivity.

3 A Model of a 5G Wireless Fixed Aerial Access Station (WiFiAAS)

The WiFiAAS design is a notable shift from the traditional mainstream terrestrial station design. 5G FWA uses the 3GPP architecture, which is widely acknowledged that enables network operators to deliver ultra-high-speed broadband to users where optical fibre is not physically possible to lay and maintain let alone be economically viable. FWA is considered as a viable alternative to optical fibre and Digital Subscriber Lines (DSL) to support homes and small businesses needing access to wireless services both in suburban and rural environments [3, 58–62].

Figure 2 gives a bird's-eye-view of the evolved aerial-to-ground network architecture which features WiFiAAS as the sky segment which is then connected to ground segments via the tethers. The helium-filled, solar-powered aerostat manages the communication payloads and wireless access using the 5G MIMO antenna. The terrestrial tethers also serve as wired communication links to both stationary and mobile users in different urban, suburban, and rural zones. WiFiAAS uses a 5G MIMO antenna with adaptive beamforming to provide a wide footprint coverage with a moderate power consumption at the 28 GHz band and with a 100 MHz bandwidth. The antenna creates MIMO beams utilizing channel conditions to maximize gain to the house thereby improving reliability and decreasing power consumption.

We use the 3D Wireless InSite tool to visualise the design of the massive 5G MIMO antenna as a planar phased array of 64 patches designed for operation at 28 GHz. The patch geometry searches for the optimum feed location to produce optimal return loss, as it affects resonant frequency and input impedance. Figure 3 shows that the feed location is calculated to be at 0.73 mm off the center point of each patch. The MIMO antenna uses adaptive beamforming with the inclusion of spatial multiplexing to improve data rates and reduce interference. Figure 4 shows the antenna geometry and specification, whilst Fig. 5 shows the gain values of the 8 × 8 patch configuration, and Fig. 6 visualizes a gain where all patches are in-phase and beamforming has been steered at different angles.

In consideration of the propagation requirements, each patch uses an adaptable phase offset to steer beamforming at various angles (°) towards the desired direction [63–66]. The main beam is calculated with Eq. (1):

$$W_n = \exp\left[-j\left(\frac{2\pi}{\lambda}\right)\sin(\theta_d)[x_n\cos(\varphi_d) + y_n\sin(\varphi_d)]\right] \quad (1)$$

where θ_d, φ_d denote phases at x_n and y_n

We utilize an optimized free-space path loss model to bridge the gap between ground users and the tethered aerostat, and calculate distance D of the optimized propagation model based on θ, which is an additional but vital consideration in calculating path loss from space like with aerial platforms. Free-space path loss is calculated with Eq. (2) and Signal to Interference Noise Ratio (SINR), and throughput (T) are calculated with Eqs. (4) through to (6):

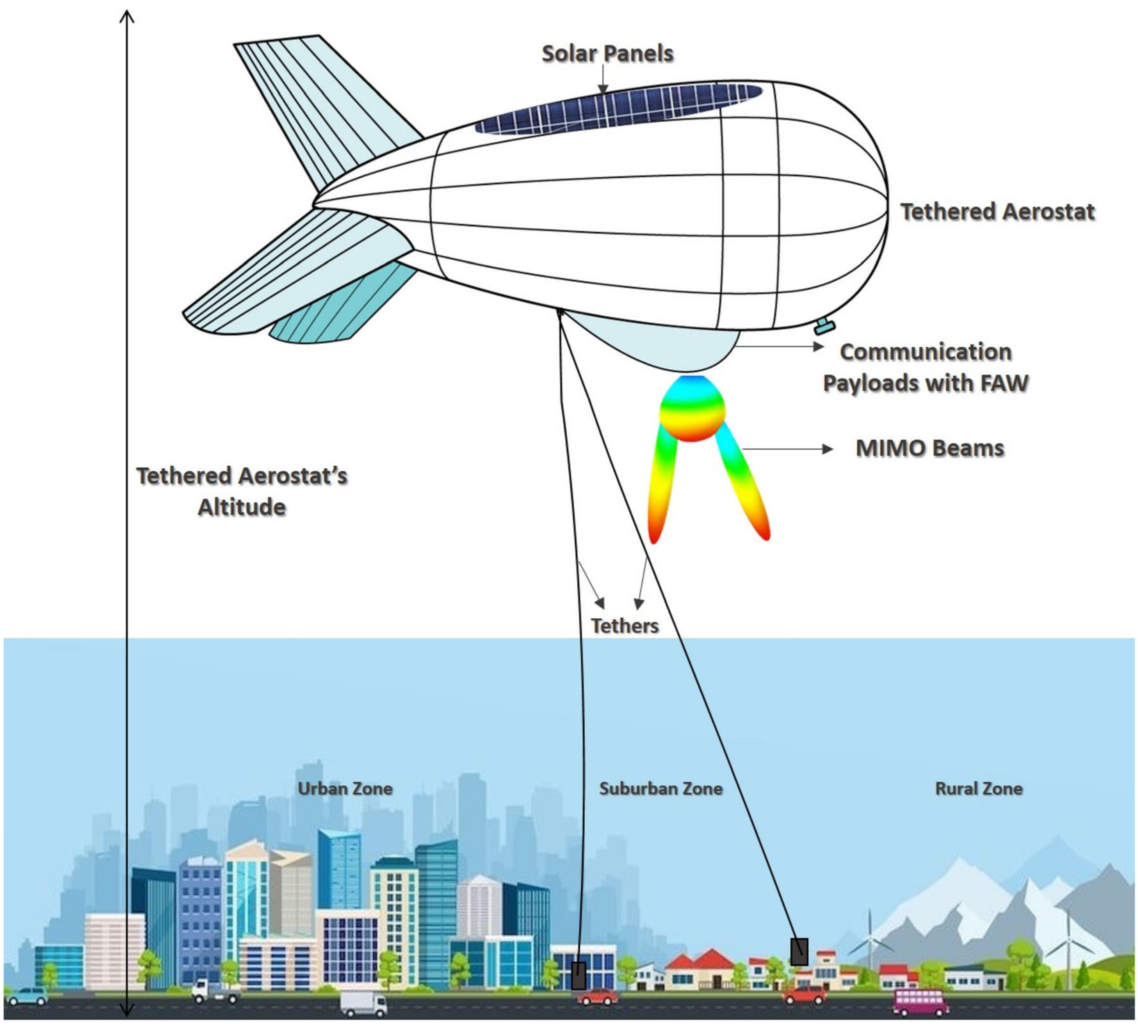

Fig. 2 The WiFiAAS over different environments

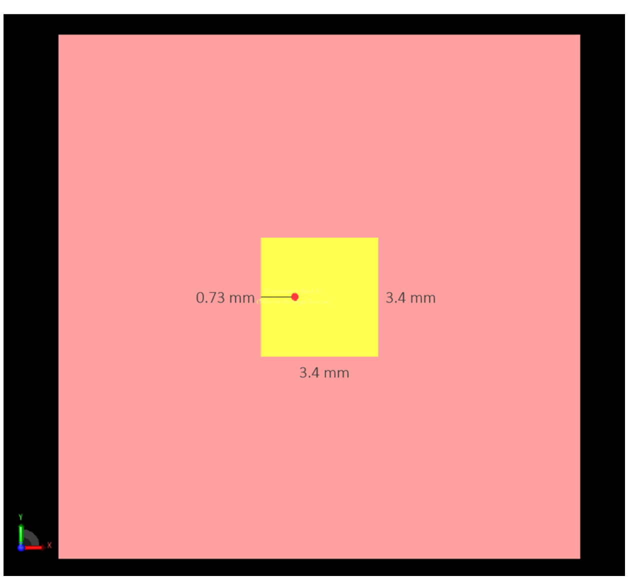

Fig. 3 The optimum feed location of the patch geometry

$$PL[\mathrm{dB}] = 40\log(\mathrm{d}) - [10\log(G_t) + 10\ \log(G_r) + 20\ \log\ (h_t) + 20\ \log\ (h_r)] \tag{2}$$

$$D = 2E_r[cos^{-1}\left(\frac{E_r}{E_r + ht} * cos(\theta)\right) - \theta] \tag{3}$$

$$SINR = \frac{RSSI}{N + I} \tag{4}$$

$$\mathrm{RSSI} = \mathrm{P_t} + \mathrm{G(h_t)} + \mathrm{G(h_r)} - \mathrm{P_L} - \mathrm{L} \tag{5}$$

$$\mathrm{T} = \mathrm{B} \times \log(1 + \mathrm{SNIR}) \tag{6}$$

where d refers to transmitter to receiver separation in km,E_r denotes the Earth's radius at 6378 km, $G(h_t)$ refers to the transmitter antenna height gain, $G(h_r)$ refers to the receiver antenna height gain, h_t refers to the tethered aerostat's altitude, h_r refers to the receiver antenna height, P_t refers to the transmitter power, L refers to the connector and cable loss, N refers to the Noise figure, RSSI refers to the received signal strength indicator, and B refers to the bandwidth [51, 62].

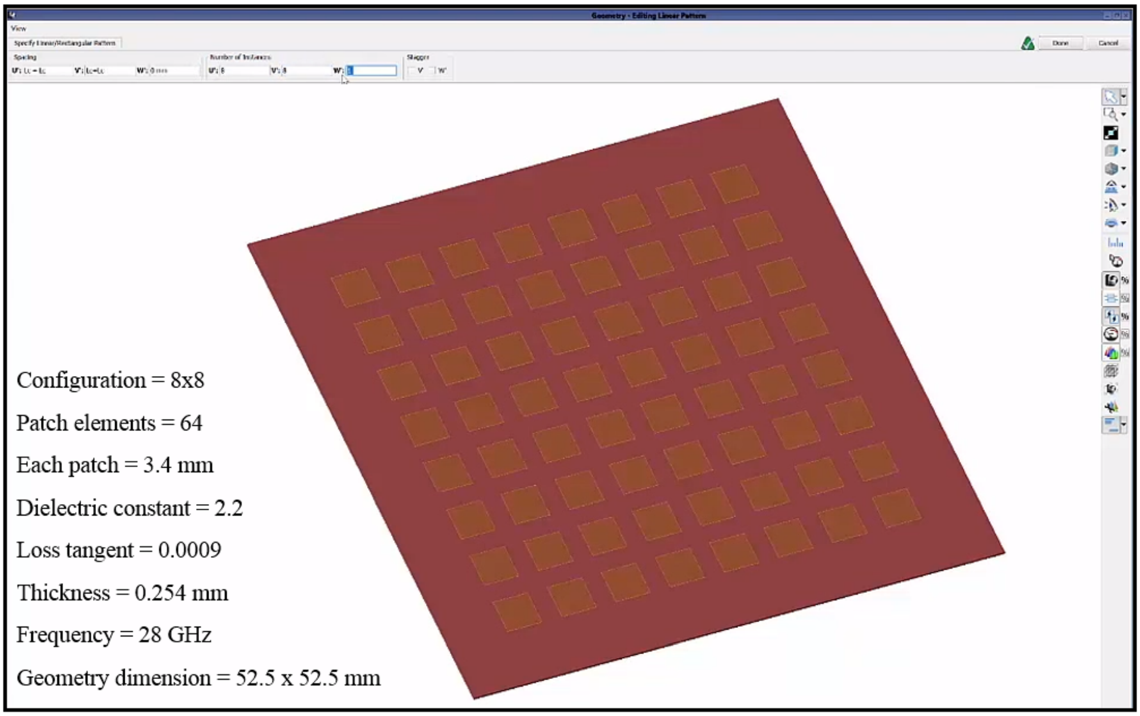

Fig. 4 The antenna geometry and specification

4 5G WiFiAAS Design Evaluation

This section uses a set of ITU-proposed 5G FWA key performance indicators to evaluate the proposed design: Reflection coefficient, CDF of EIRP, path loss, throughput, SINR against radiation patterns, and RSSI [3, 10–21]. The ITU advises on different sets of key performance indicators depending on the assessment objective and our literature review reveals that this advice has been widely practiced.

Figures 7, 8, 9, 10, 11, 12 depict collectively the performance assessment of the 5G MIMO antenna on-board the aerostat. Figure 7 shows the reflection coefficient S11 which measures the amount of power reflected from the antenna because of the antenna geometry. The figure shows the radiation power with a low loss at 28 GHz which is within the acceptable range. The S parameter measures the resonant frequency of the antenna in relation to the resonance of the TM12 mode inside the cavity and the TE mode to establish the ratio between reflection and transmission. Figure 8 represents the CDF of the EIRP. The figure plots the cumulative probabilities against power and shows an array coverage of about 72% with a positive gain at 23dBmW of input power. The maximum allowable path loss allows the maximum cell range to be estimated in consideration of the propagation model.

Figure 9 shows the PL values as a function of distance and at various frequencies. The MAPL for the 5G MIMO antenna is set at 140 dB, therefore the distance at 28 GHz reaches 18.5 km. Clearly, PL increases with distance values as shown on the figure. It is notable that as frequency increases PL increases, due to power absorption at higher frequencies. Figure 10 presents the T values as a function of distance at various frequencies. Throughput decreases with distance as well as with higher PL. At 18.5 km the antenna generates a throughput of around 350 Mb/s, which in turn meets the MAPL of 140 dB.

The SINR is commonly used in wireless communications to assess the quality of a wireless link and bit error ratio. Figure 11 illustrates that the SINR ranges between 7 and 33 dB across different beamforming. Beamforming currently in use includes boresight, 60° beam, full sweep, and adaptive. SINR values below 5 dB are regarded as inadequate, whilst any value above 40 dB wastes transmission power. With adaptive beamforming SINR gives reasonable results especially at beam coverage with azimuth ranges between 0 and 150°. The advantage of adaptive beamforming is that adjusting the main lobe to focus on the direction of arrival of the desired signal, reduces signal interference. Figure 12 visualizes in 3D the suburban RSSI. As PL increases the RSSI decreases with distance, geomorphology, and multipath. LoS connectivity from that altitude is the key reason why RSS floats within the acceptable average of 65 dB and with moderate power consumption. Increasing the altitude might yield better LoS connectivity and in turn decrease shadowing. However, PL

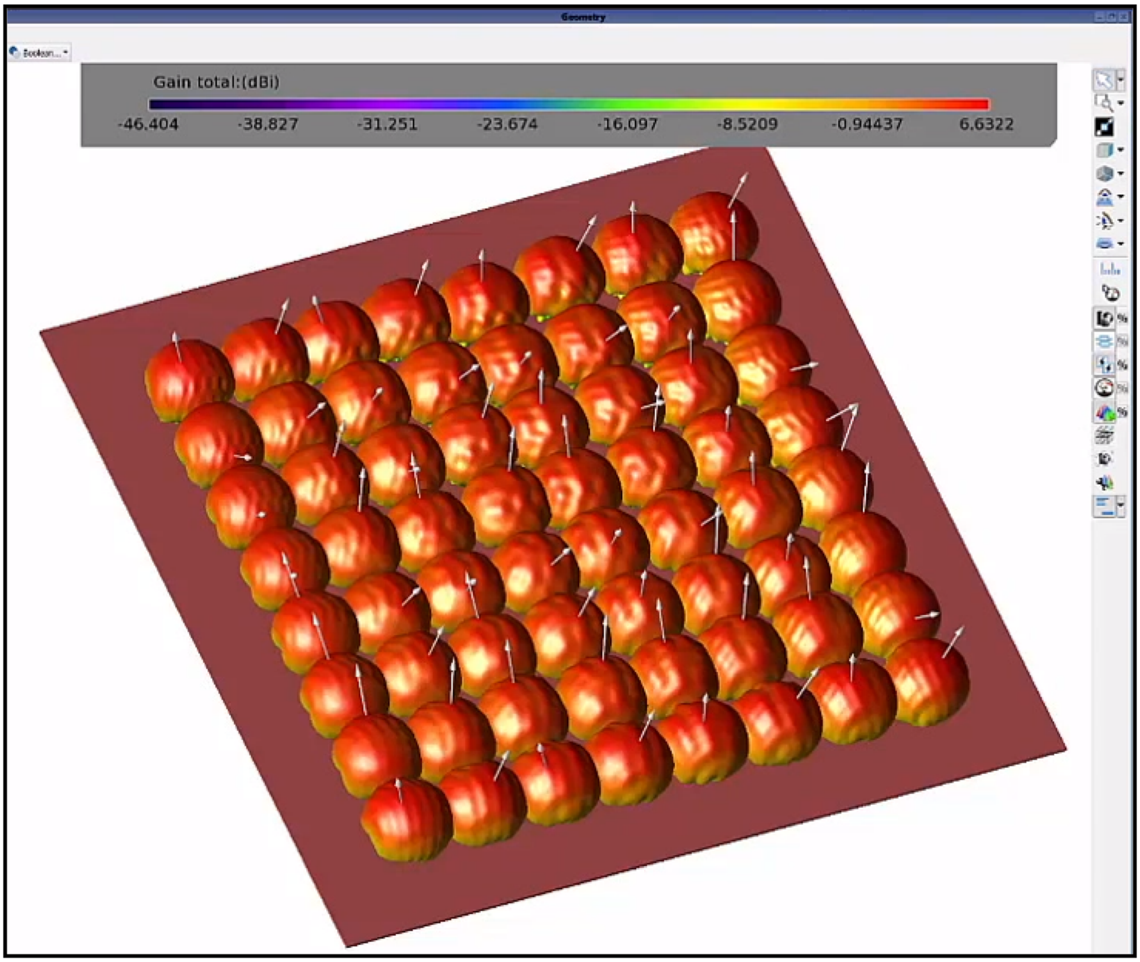

Fig. 5 The antenna configuration gain values

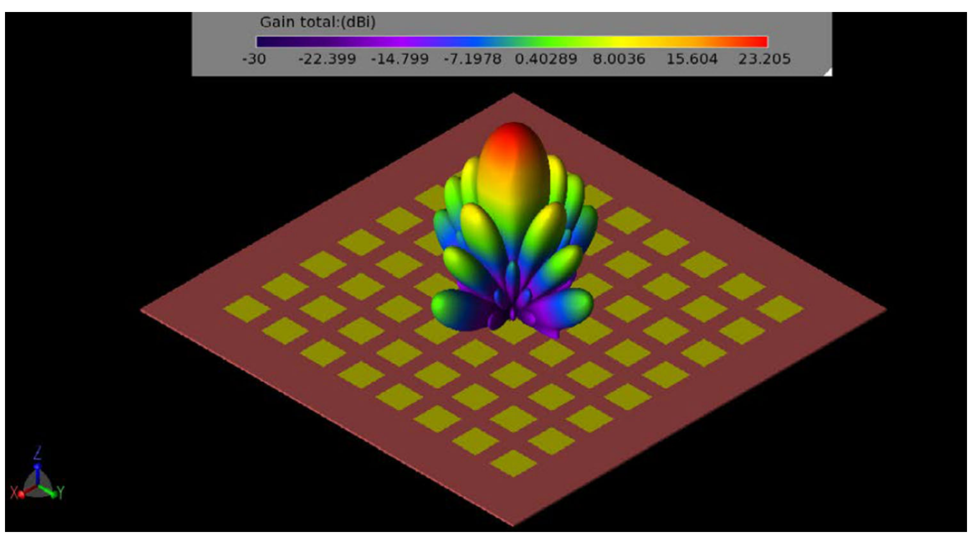

Fig. 6 Antenna gain with all patches in-phase and beamforming steered at different angles

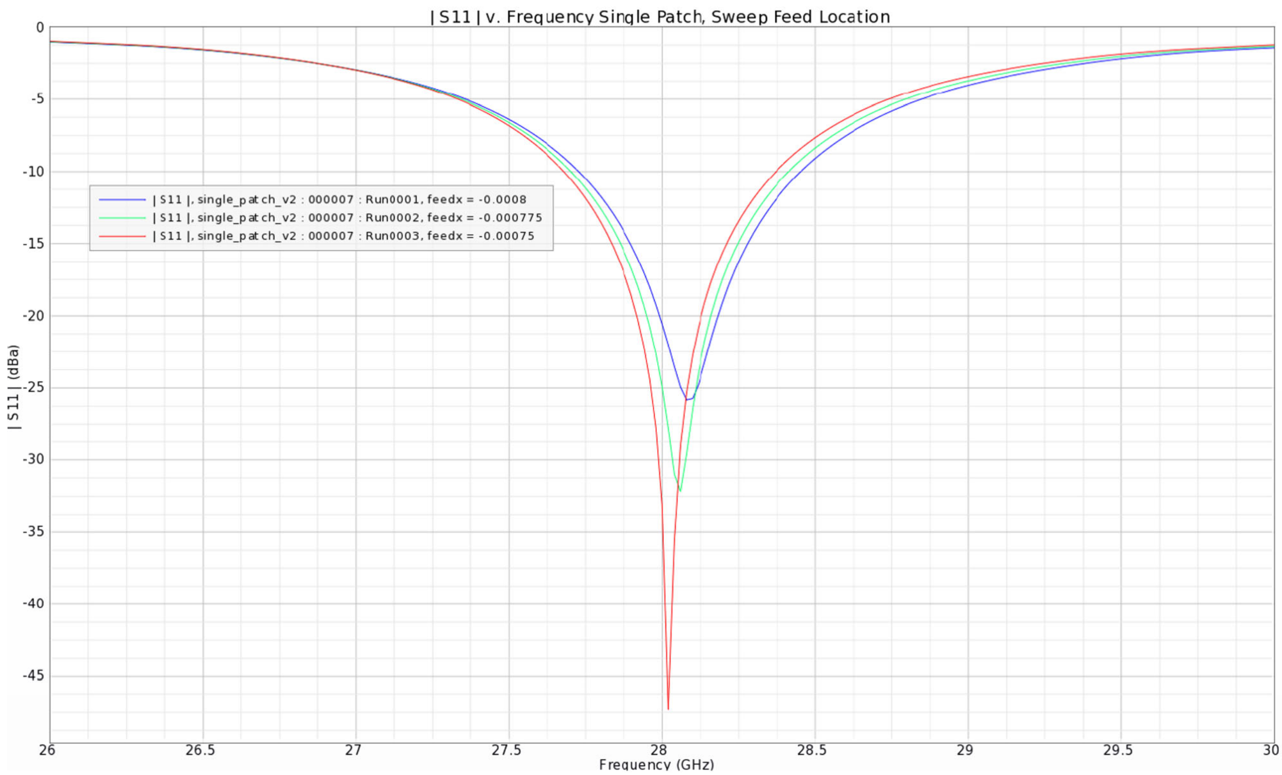

Fig. 7 5G MIMO antenna S11 results

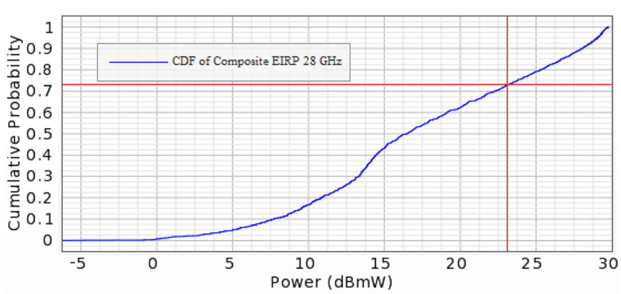

Fig. 8 5G MIMO antenna CDF of EIRP

increases with distance too. Thus, a compromise is vital to achieve a reliable communication link.

5 5G WiFiAAS Proof-of-Concept Application Validation

This section validates the WiFiAAS design and the 5G MIMO Antenna through a WSN that includes such an Aerial Access Station. The WSN supports a wide range of mostly IoE applications, from disaster relief to smart security surveillance, to smart traffic control, to smart farming, with several ground sensors collecting ground segment data as Fig. 13a shows. Figure 13b shows a typical everyday use of the WSN for smart farming in one of the project smart farms. Four families of ground wireless sensors each collect data on soil moisture, air humidity, air temperature, and local water levels in support of crop irrigation. The sensors use the Message Queuing Telemetry Transport (MQTT) protocol to communicate their data to the Aerial Access station for edge processing. Figure 13c illustrates the visualization of some of the edge node processed data on the Blynk IoT platform to help support the project farmer with their crop monitoring on the project land and in turn the goal of precision agriculture. The project farmer may use Blynk in return, from remote resetting of one or more sensor threshold values to commencing water irrigation of the entire or part of the field, on the demand of the crop, based on sensor data.

The link quality between the Aerial Access Station and the ground sensors depends on a number of key factors including the aerostat altitude, operation frequency, transmission power, transmitter and receiver antenna gains, bit rate, and link distance between the aerostat and the sensors. The use of the 5G MIMO antenna results in extending the coverage range, reducing path loss and fading, improving power consumption with low propagation loss and high RSSI without the use of external power sources. We use the two key QoS performance indicators of the power spectral density ratio of Eb/No and the BER of an AWGN Channel to assess performance [47]. These indicators are calculated with Eqs. (7) through to (11):

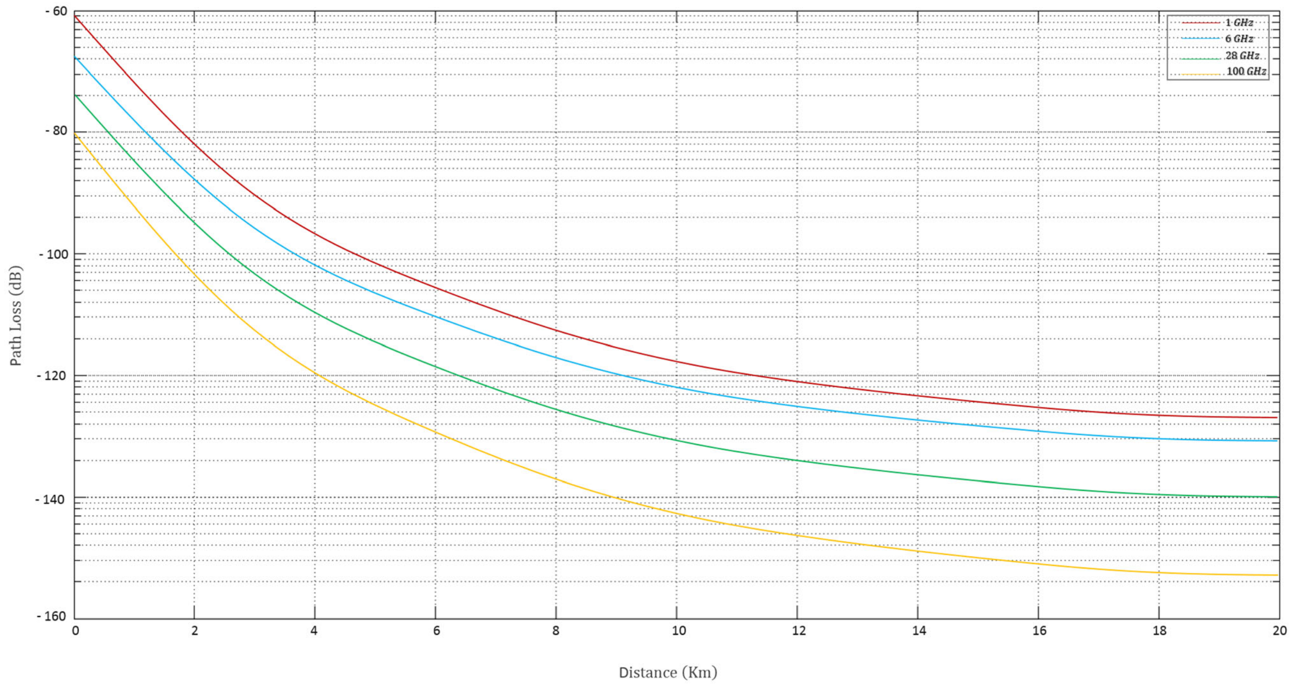

Fig. 9 Path loss against distance at various frequencies

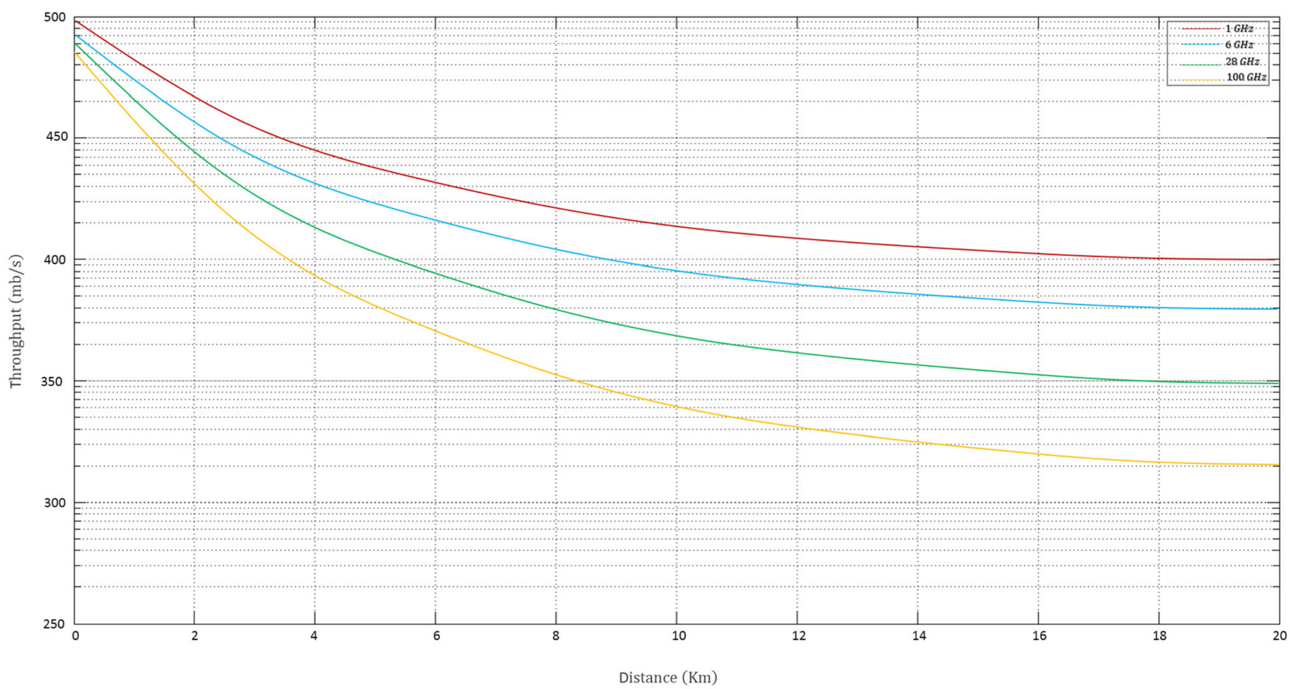

Fig. 10 Throughput against distance at various frequencies

$$\frac{E_b}{N_0} = \frac{C}{N} + 10\log BW - 10\log R_b \tag{7}$$

$$\frac{C}{N} = EIRP - P_L - A_R + \left(\frac{G}{T}\right) - 10\log\frac{KBw}{0.001} \tag{8}$$

$$EIRP = P_t + G_t + G_r - L \tag{9}$$

$$\frac{G}{T} = G_r - 10\log T \tag{10}$$

$$BER = \frac{1}{2}erfc\sqrt{\frac{E_b}{N_0}} \tag{11}$$

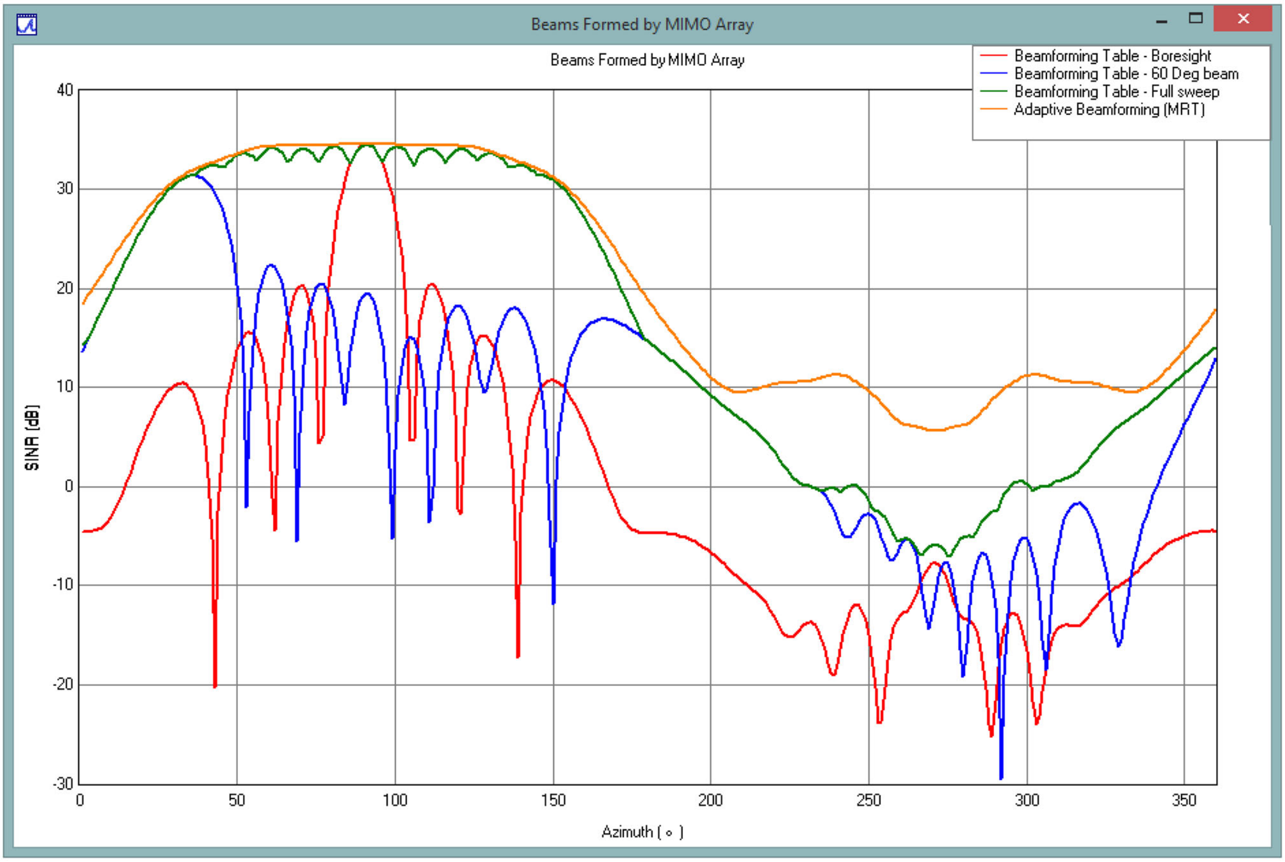

Fig. 11 SINR against Azimuth at various radiation patterns

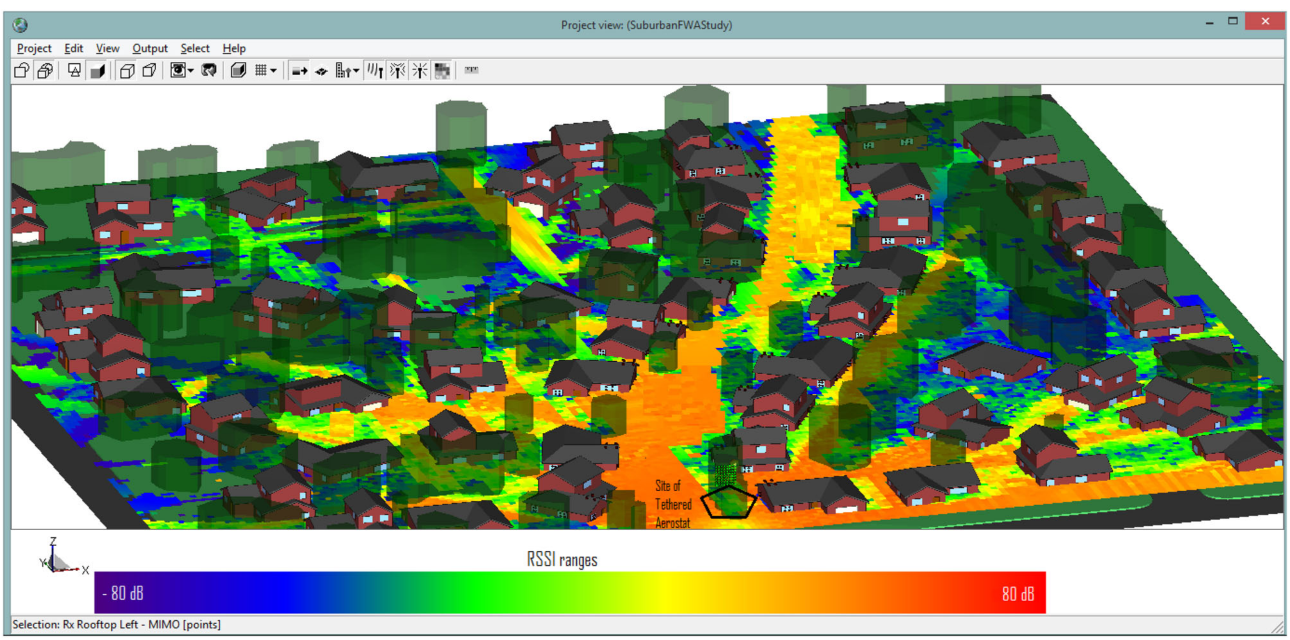

Fig. 12 Suburban RSSI in 3D scenario at an altitude of 200 m

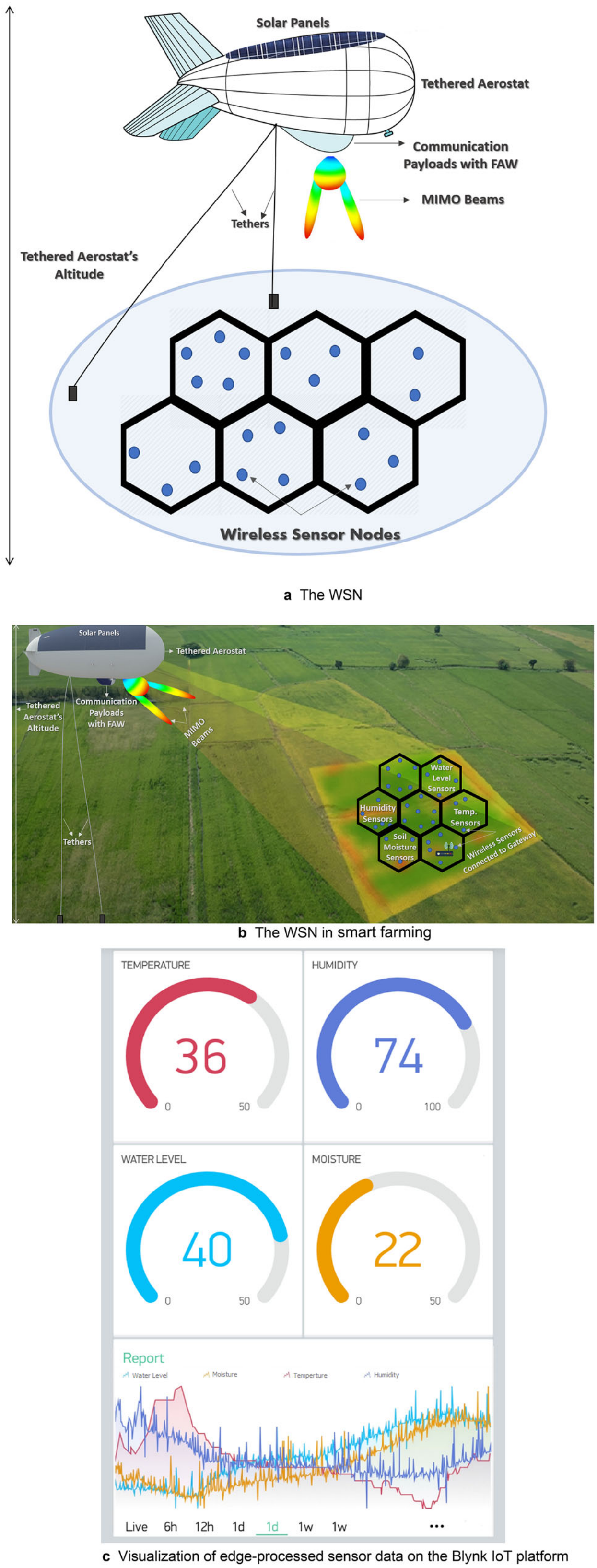

Fig. 13 **a** The WSN. **b** The WSN in smart farming. **c** Visualization of edge-processed sensor data on the Blynk IoT platform

where EIRP refers to the Effective Isotropic Radiated Power, C/N refers to the carrier power measured in dB, BW refers to the bandwidth measured in Hz, R_b refers to the data rate, P_t refers to the transmitter power , G_t refers to the transmitter antenna gains, G_r refers to the receiver antenna gains, L refers to the connector and cable loss, A_R refers to the rain and atmospheric gas attenuations which are negligible, K refers to the Boltzmann's constant, G/T refers to the ratio of the receiver antenna gain to the system noise temperature measured in dB0, T refers to an affective temperature which in this WSN is set at 310 K, and *erfc* refers to a complementary error function that describes the cumulative probability curve of a Gaussian distribution. Predicting and reporting additional Eb/No and BER results is carried out using the "semilogy" function in MATLAB.

Table 2 and Fig. 14 compare the predicted Eb/No and BER values of an AWGN channel with a directional and an omnidirectional antenna against the **actual** results of the 5G MIMO antenna on-board the Aerostat. Figure 14 shows the Eb/No performance across the three antenna types at the lowest BER achieved of 1×10^{-6}. The two QoS indicators indicate a reasonable performance for the 5G MIMO antenna. As the Eb/No and BER values decrease, wireless link performance increases which suggest a channel with low error rates and using minimum transmission power. This is largely due to the diversity gain of the 5G MIMO antenna which results in maximizing capacity and the link budget, improving the coverage range without increasing the transmission power between the aerostat and the wireless sensors and with moderate path loss and fading. The results support the findings reported on Table 1.

6 Concluding Discussion

This paper presents the model of a 5G Wireless Fixed Aerial Access Station that stems from the design and mounting of a 5G MIMO antenna on a tethered aerostat. The model supports fast deployment and re-deployment, wider coverage, reduced power consumption, and offers last mile connectivity to both mobile and stationary users as it supports both wired connectivity using the tethers attached to it and wireless connectivity at both LoS and nLoS.

Table 2 BER of a signal as a function of Eb/No across the three antenna types

QoS indicators	Directional	Omnidirectional	5G MIMO
BER	1×10^{-6}	1×10^{-6}	1×10^{-6}
Eb/No (dB)	**21**	**15.9**	**12.5**

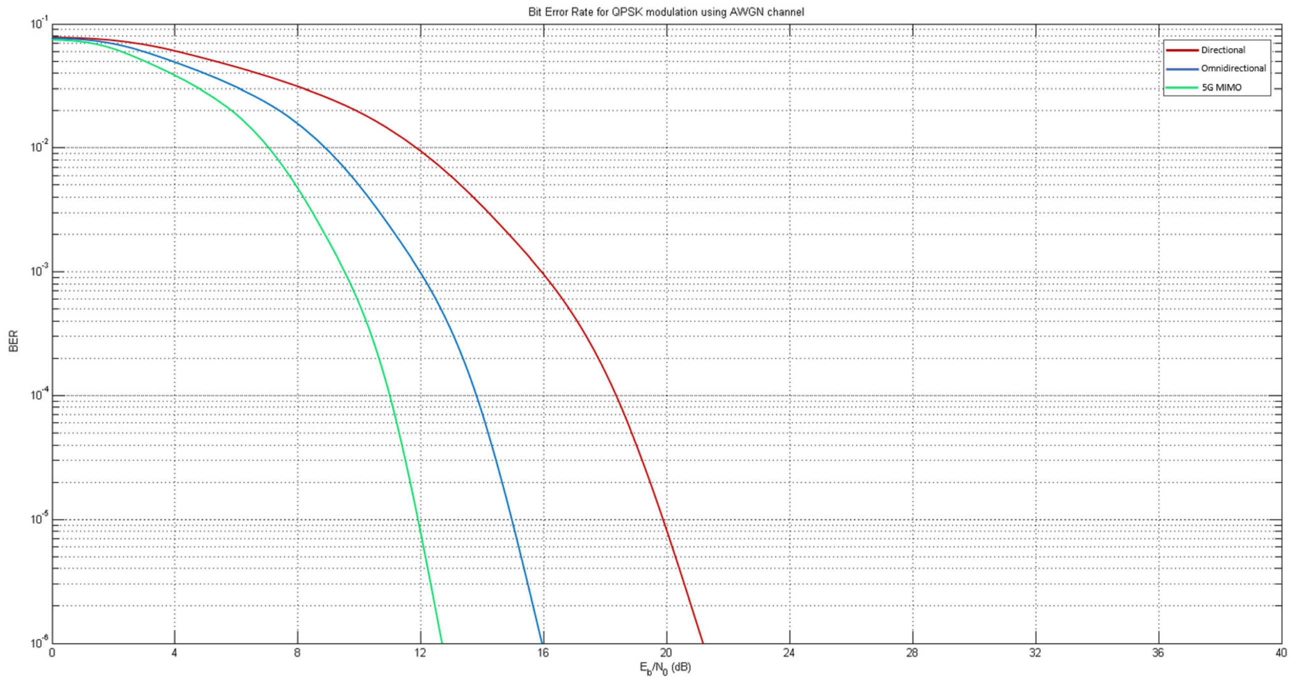

Fig. 14 BER of a signal as a function of Eb/No across the three antenna types

The performance evaluation of the 5G MIMO antenna on-board the WiFiAAS reveals efficiencies in relation to S11, and CDF and actual results indicate that the link budget parameters of PL, T, SINR, and RSSI provide efficient last mile connectivity. The paper exploits the efficiencies that unfold and uses the model in several proof-of-concept applications in an existing WSN.

A model like WiFiAAS which represents a significant shift from mainstream approaches will become a competitive advantage in the hands of Internet Service and Content Providers as it does not rely exclusively on terrestrial base stations or satellites and, in comparison to the more expensive and permanent satellite approach, it offers added-value as it is more cost-effective, with technical maintenance nowhere near as complex as a satellite [67].

Future work, when the pandemic restrictions would allow, may stretch to assessing the impact of environmental factors and to prototyping outdoor applications all as part of live projects.

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