''Techno-economical study of the antenna system weight, wind load and space occupancy in view of the mobile network transition to the 5G era and beyond.''

Sub-theme: Session 1: Optical Networks and Infrastructures

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Abstract

Telecommunication towers represent significant economic factors that directly influence the quality of most wireless telecommunication services worldwide. That is reflected on the extensive work both academia and industry perform for the continuous improvement of telecommunication tower infrastructure mainly in terms of structural optimization of tower structures and reinforcements. The transition to the 5G era brings about a significant increase of the overall volume and weight of installed tower-top equipment on old existing tower infrastructure that in turn raises the uncertainty of their structural integrity under over-loading conditions. Furthermore, recent developments in Europe, concerning transfer of tower asset ownership from mobile network operators to tower companies, the principal economic driver for increasing tenancy ratio, yields similar questions. The present work focuses on the quantification of the antenna system importance on the structural integrity of existing or new installation sites by calculating its contribution on the overall weights and wind loads acting on the telecommunication tower. The antenna system is herein considered as the transmitting antenna and its tower mounting equipment that for the purpose of this study are accounted in combination as a system. This work considers self – supported lattice towers and monopole structures of low to medium height. Using finite element calculations along with ANSI/TIA 222 and the relevant Eurocode guidelines, the reduction of the antenna system size, surface, and weight results in significant reduction of the wind and weight loads of the installed equipment on tower-top's reaching up to 40% per tower rad center, projected onto selected fully loaded tower case studies. Such wind and weight load reductions can in turn be exploited in a variety of ways, including smooth and economic site upgrades to 5G equipment or beyond, increasing the tower's tenancy ratios or the tower-top installed equipment in general, while improving the tower's safety margin without the need for reinforcements or massive tower redesign operations that can be proven quite costly and time consuming.

A thorough investigation of the financial benefit of the replacement of heavy, bulky industrially popular antenna mounting systems is performed resulting in potentially high and significant profit margins for all involved stakeholders as shown extensively throughout the present work.

1. Introduction

It is only around 40 years since the birth of mobile telephony and in that time the capabilities of cellular networks have evolved at a pace which has fueled both social change and innovation on a global scale while going hand in hand with economic growth factors [1-5]. From 2G (voice) to 3G (image) to 4G (video), technological advances drive ever increasing data consumption requirements. 5G supports significantly faster mobile broadband speeds and lower latencies than previous generations while also enabling the full potential of the Internet of Things. Connected cars to autonomous vehicles, transforming healthcare to building smart cities, factories and homes, while providing fibre-over-the-air network speeds to consumers [6], 5G is at the heart of the future of communications. However, the deployment of either stand-alone 5G networks in the long-term, or of non-standalone 5G networks (i.e. collocated with existing 3G/4G technologies) in the short to mid-term, both require the installation of more, bulkier and heavier antennas and antenna near equipment on the telecommunication towers. Moreover, the newly constructed towers get over dimensioned in order to support the projected load. To make things worse, the global trend of transferring the ownership of tower assets to tower companies that can operate these assets more efficiently, leads to the need for increasing the tower's tenancy ratio (i.e. the average number of tenant networks supported by a tower).

However, the process of adding loads on towers (due to 5G upgrades and/or tenancy increase) is finite. Since after a certain amount of loading that depends on the tower's initial structural dimensioning, the imposed loads will eventually exceed the tower's static capacity. This is even more crucial for legacy tower builds that have been designed, dimensioned and constructed years ago in order to support significantly fewer loads. The excess of static loading imposed on them to support 5G infrastructure and more tenants sets their static integrity/adequacy under question thus demanding immediate action (reinforcements) to avoid catastrophic failure and to comply with the standing standards and legislation [7]. In consequence, excessive research is performed in order to model the static and dynamic behavior of telecommunication towers as shown in the works of Goral and Barelikar [8], Preeti and Dhoopam [9] and Al–jassani and Al-Suraifi [10]. Furthermore, the international literature focuses on two main categories, namely tower design optimization and reinforcement techniques.

Tower design optimization techniques apply solely to new tower installations and include methodologies such as the work of Tsavdaridis et al. [11] who presented a topology optimization method for the design of telecommunication towers, Tessari et. al. [12] that presented a design methodology to predict various uncertainties occurring during the design phase and Khodzhaiev and Reuter [13] who presented a genetic algorithm-based methodology of structural optimization. Other works on steel tower optimization include Tort et al. [14] that achieved significant weight reduction through industrially used optimization techniques and de Souza et al. [15] that included bolt slippage effects in their optimization procedure.

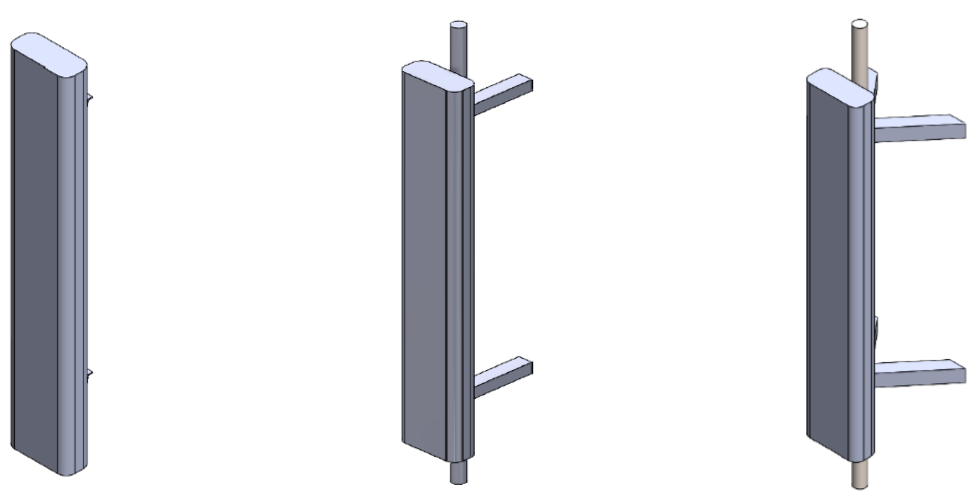
In the case of existing telecommunication towers, in order to increase their structural integrity or their load capacity, reinforcement works are usually applied throughout the industry. Typically used reinforcement methods include the reinforcement of the tower legs [16] or the bracings [17 - 19], however as Winkelmann and Duch [20] show in their work, applying curbs and braces reinforcement techniques on telecommunications towers can increase the safety margin by a limited amount (up to 19% per case) independent of the legs and bracings cross section increase in percentage. The significance of this finding is enhanced by the case study presented in the work of Johansyah and Munthe [21] who demonstrate the increase of the tower load by almost 20% above its original load capacity as a result of an upgrade involving increased height and the inclusion of a single additional antenna unit. In terms of evaluating the structural condition and remaining lifespan of existing telecommunications towers in order to avoid catastrophic failure and proceed to maintenance actions, spectral analysis is used widely [22-23]. Catastrophic failures of lattice towers as a result of overloading are also modelled and experimentally tested [24], [25] in order to predict and most importantly prevent such occurrences.

Contrary to the presented literature modelling and reinforcing techniques that tend to neglect the effect of auxiliary equipment, the present work aims to introduce an innovative alternative approach to increase the static load capacity of telecommunications towers via tower offloading through the minimization of the volume and weight of the antenna system focusing on the antenna mounting brackets. Detailed FEA and CFD modeling of the antenna system is performed and their contribution to wind loads acting on a model tower is quantified. These wind loads are used to calculate the resulting bending and buckling loads on the structural members of the tower. Comparison between the antenna mounting brackets currently used in the industry and a newly proposed with the purpose to improve antenna system loading [26 - 27] is performed and applied in various case studies. The findings demonstrate a significant force reduction induced on the tower of up to 35% – and load capacity increase in consequence – dependent on the case study.

At this point it should be mentioned that the proposed antenna mounting offloading solution is also space efficient since it drastically minimizes the antenna system volume enabling more antennas and antenna near products to be installed on the tower RAD center, while it does not compromise the network performance by decreasing the antenna or RRUs installation height on tower. The innovativeness of such offloading practice, as thoroughly analyzed on the present work, is also highlighted by the current trend followed by antenna manufacturers to involve computational tools and experimental testing complimentarily to the conservative international standards such as TIA-222-H and the relevant Eurocodes, to calculate the actual wind loads acting on antenna systems [28], to improve the aerodynamic design of antennas [29] not missing to account for the antenna mounting poles on their calculations of the resulting wind loads considering the pole unshielded for the entire length of the antenna [30-33].

2. Modelling and simulation of the antenna-bracket system

As already mentioned, the present work considers the effect of the antenna mounting on the resulting wind and weight loads on the telecommunication tower. A comparative study is performed between the antenna mounting brackets currently used and the newly proposed. The antenna – bracket system considered for the purposes of this study is shown in Figure (1) below. The antenna selected is of panel type with LxWxD (Length, Width, Depth) dimensions of 2000x350x150 (mm) while its weight is accounted to be 50 [kg]. The selected antenna corresponds to a commonly used by mobile network operators multiband 4G/5G antenna. The antenna has not been modeled as a rectangular box, (appropriate radii has been applied at the edges of the model) as such to account for the improved drag coefficient commercially available antennas achieve. The dimensions of the remote radio units (RRU) considered throughout the present study are 400x300x150 (mm) while their weight is accounted to be at 14 [kg]. The selected remote radio unit (RRU) dimensions and weight correspond to commonly deployed RRUs on 4G radio networks. 4 RRUs (one per band) are considered per multiband antenna installed on tower. The coaxial cables that connect each RRU to the antenna are considered to be of ½” diameter, while their density is considered equal to 0,21Kgr/m. The selected RF cable type corresponds to commonly used by the industry for the RRU - antenna interconnection.



a) (b) (c)

Figure (1): CAD models of antenna – bracket systems used throughout the present study. (a) antenna with the newly proposed bracket, (b) antenna with currently in use bracket - Type 1, (c) antenna with currently in use bracket - Type 2.

Table (1) provides the basic dimensional characteristics and weights of both the newly proposed bracket and the currently in use one (Type 1 and Type 2). It is obvious that the current bracket embeds the use of mounting poles that significantly increase the effected projected area and the weight of the antenna system. The antenna is mounted on the pole by a set of mounting collars located at the antenna's backplane, capable to allow antenna azimuth alignment. The length and the diameter of the mounting pole is selected as per the international standards [34], in order to provide adequate clamping force to satisfy vertical and horizontal non-sliding condition of the antenna under loading conditions. It is worth mentioning here that when following antenna manufacturer instructions [35] for the installation of antennas with length over 1575mm, the minimum recommended pipe diameter should be at least of 70mm. The set of spacer bracket arms offer the necessary distance of the antenna from the tower structure to prevent the antenna from clashing on the tower while also providing the necessary space for a rigger to work on during the alignment process at installation phase. It has to be mentioned that the antenna mounting brackets accounted for the purposes of this study (both Type 1 and Type 2 of Figure (1)) are widely used in the industry globally.

Table 1: Antenna mounting bracket dimensions and weight comparison

	Newly Proposed	**Currently in use Type 1**	**Currently in use Type 2**
Height [m]	0.1	0.05	0.08
Length [m]	0.15	0.4	0.47
Width [m]	0.1	0.1	0.1
No of parts	2	2	4
Pole height [m]	-	2.6	2.6

Pole outer diameter [m]	-	0.072	0.072
Total weight [kg]	4	30	47

Figure (2) shows the height-independent modelling of the telecommunications tower. The tower consists of unitary structural elements (unit cells) of equal height (h_e) and dimensions. F_i is the wind load acting on each unitary cell and M_i is the moment acting on the tower base as a result of the respective wind load F_i. W_i is the total weight of each unit cell including any existing equipment. It goes without saying that the same procedure can be applied regardless of the selection of structural components for any self-supporting lattice tower, without loss of generality.

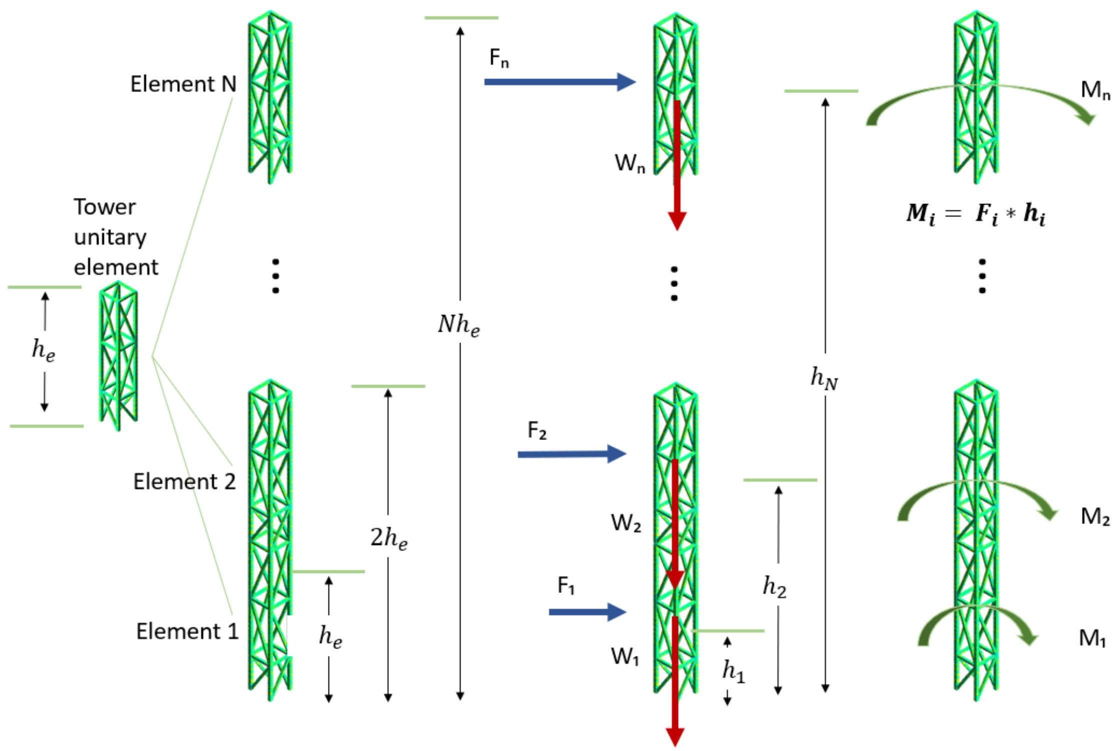


Figure (2): Modelling of the tower loads.

Since all simulations presented in this work consider self-supported lattice towers with constant unit cells the total loads are taken at the base of the tower. Eq. (1) shows the total bending moment acting on the base of the tower.

$$M_{total} = \sum_{i=1}^{N} (2i-1) h_e \frac{F_i}{2} \quad (1)$$

, where N is the total number of unit cells.

The comparative analyses presented below focus on three potential failure mechanisms of telecommunications towers namely the bending moment, critical buckling load and the serviceability limit state (SLS) that depends on the deformation of the tower top. Calculation of the critical buckling load (F_{Pcr}) is performed in accordance with Zhao et al. [36] considering stiff joints as shown in Eq. (2) below. The critical buckling load is initially compared with the total weight of the tower including the installed equipment.

$$F_{Pcr} = \frac{\pi^2 EI}{H^2} \frac{1}{4 + \frac{\pi^2}{8}\left(\frac{b}{H}\right)^2 \frac{A_1}{A_2 \sin\theta \cos^2\theta}} \tag{2}$$

where E is the Young's modulus of the tower material, H is the total height of the tower, b is the length of the quadrilateral tower side, A_i is the cross section of the leg and brace members and θ is the angle between the diagonal and horizontal brace. $I = A_1 b^2$ is the moment of inertia of the quadrilateral tower with respect to the centroid axis. F_{PCr} is then compared to the total weight acting on the tower legs including the compressive loads from the bending moment as in Eq. (3) to calculate the buckling safety margin variations.

$$\frac{F_{Pcr}}{W_{total} + \frac{M_{total}}{b}} = S_{f,buckling} \tag{3}$$

A rough estimation of the deformation of the tower top is performed though a cantilever beam modelling using the horizontal loads acting on the unit cells and the equivalent moment of inertia I.

Calculation of the wind loads is performed at 0 and 45-degrees as per the international standards and the average values are compared. The antenna – bracket systems are installed on a unit cell and computational fluid dynamics (CFD) simulations are performed considering uniform wind speed equal to 45 [m/s]. All simulations were performed using ANSYS CFX.

The simulation results presented in Figure (3) below on a standalone antenna system, prove that the application of the newly proposed brackets provide a 24% reduction of the maximum antenna system wind load and a 33% reduction of the antenna system weight as compared to the currently used Type 1 brackets (707N vs 928N and 54kg vs 80kg), while it provides a 27% reduction of the maximum antenna system wind load and a 44% reduction of the antenna system weight as compared to the currently used Type 2 brackets (707N vs 969N and 54kg vs 97kg).

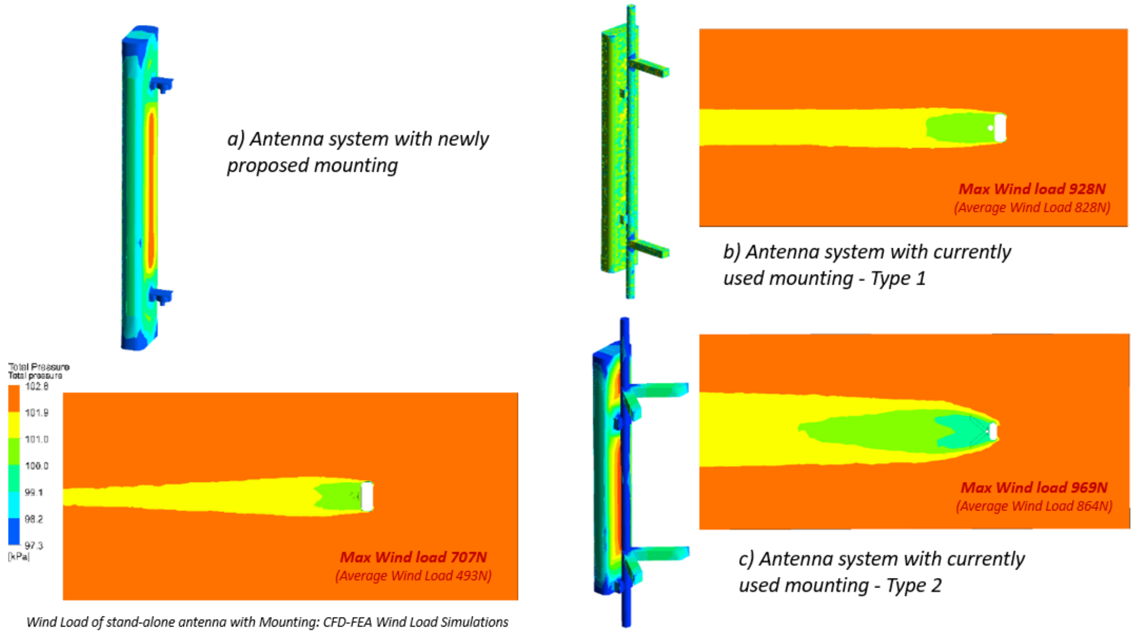


Figure (3): Wind pressure acting on standalone antenna and (a) the newly proposed bracket, (b) currently in use bracket - Type 1, (c) currently in use bracket - Type 2.

3. Results and discussion

Two case studies are herein presented, a lattice tower of 15-meter height that consists of four unit cells having 3.7-meter length each, the dimensions of which are given in Table (2) below. The selected lattice tower (and height) corresponds to a commonly used tower type widely deployed on semi-rural radio clusters. All legs and braces are square beams.

Table 2: Lattice tower unit cell characteristics.

	Length [m]	Width [m]	Thickness [m]
Diagonal Bracers (Long) – 8x	1.65	0.06	0.007
Horizontal bracers – 12x	0.68	0.06	0.007
Legs (Long) – 8x	1.5	0.08	0.008
Diagonal Bracers (Short) – 4x	1.13	0.06	0.007
Legs (short) – 4x	0.9	0.08	0.008

A reference tower (REF_{tower}) is modelled using the Type 2 bracket and four antennas placed at the tower top unit cell (unit cell shown in Figure (4)). Sixteen RRUs are considered to be installed at ground level thus not contributing to the wind and weight loads. A pair of coaxial cables per RRU is considered for the interconnection with the antenna, while the RF cable contribution to the wind load has been neglected.

Substitution of the Type 2 bracket with the newly proposed bracket (CONFIG_1) provides the comparative results shown in Table (3). For bending moments calculation, the maximum simulated values of wind load have been considered.

Table 3: Comparative results between REF_{tower} and CONFIG_1.

	REF_{tower}	**CONFIG_1**	**Percentile Difference (%)**
Total weight [kg]	1736	1563	**-10.0**
Center of mass [m]	9.6	9.1	**-5.1**
Bending moment [kNm]	123.4	110.5	**-10.5**
$S_{f,buckling}$	10.80	12.06	**11.6**
Deflection [mm]	33	30	**-11.3**

It is obvious from the contents of Table (3) that there is significant reduction of the critical stress limit parameters of the reference tower increasing its existing capacity. An alternative setup (CONFIG_2) where the 16 RRUs are also moved to the tower top thus decreasing RF losses and improving the network performance, was also compared against the reference tower case.

Table 4: Comparative results between REF_{tower} and CONFIG_2.

	REF_{tower}	**CONFIG_2**	**Percentile Difference (%)**
Total weight [kg]	1736	1720	**-0.9**
Center of mass [m]	9.6	9.5	**-0.4**
Bending moment [kNm]	123.4	114.5	**-7.3**
$S_{f,buckling}$	10.80	11.58	**7.2**
Deflection [mm]	33	31	**-7.9**

As shown in Table (4) moving the RRUs at the tower top is feasible in terms of the strength criteria presented earlier even allowing for additional margins. It can be shown that the contribution of the tower top unit cell (antenna placement) contributes more than 50% of the total bending load (REF_{tower}) while it accounts for the 40% of the total bending moment of CONFIG_1 and CONFIG_2. That being said, the contribution of the tower top would be even more significant in towers of lower heights while its contribution is expected to decrease in towers of higher heights.

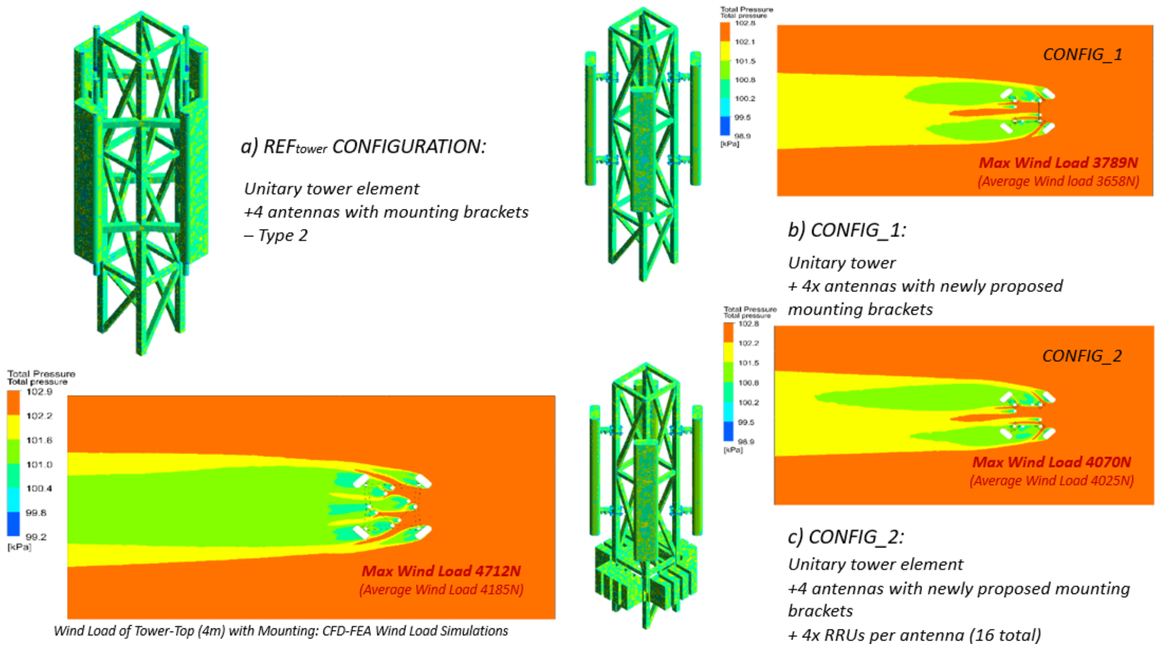


Figure (4): Wind pressure acting on lattice segment. (a) REF_{tower}, (b) CONFIG_1, (c) CONFIG_2.

The same process was also performed on a 10-meter-high monopole of 114mm outer diameter deployed with three antennas. The selected monopole tower (and height) corresponds to a tower type widely used on urban radio clusters. Again, a comparison was performed with the aforementioned reference monopole having the 3 antenna systems equipped with Type 1 brackets (REF_{mono}) not including the RRUS at the monopole top, to 3 antenna systems equipped with the newly proposed brackets also not including the RRUS at the monopole top (CONFIG_1m). A second configuration monopole was also examined having the 3 antenna systems equipped with the newly proposed brackets but with 12 RRUs installed on tower top level just below the antennas (CONFIG_2m). A pair of coaxial cables per RRU is considered for the interconnection with the antennas (6 per antenna, 18 RF cables in total), while the RF cable contribution to the wind load has been neglected. The cumulative comparative results are presented in Table (5), while the CFD simulations are presented in Figure (5).

Table 5: Comparative results between REF_{mono} , CONFIG_1m and CONFIG_2m.

	REF_{mono}	**CONFIG_1m**	**Percentile Difference (%)**	**CONFIG_2m**	**Percentile Difference (%)**
Total weight [kg]	751	672	**-10.0**	810	**7.8**
Center of mass [m]	6.1	5.9	**-3.7**	6.2	**2.3**
Bending moment [kNm]	15.7	10.7	**-31.8**	15.2	**-3.4**
$S_{f,buckling}$	2.79	3.12	**11.7**	2.59	**-7.3**
Deflection [mm]	370	242	**-34.6**	357	**-3.7**

As shown in Table (5) by the substitution of the Type 1 brackets with the newly proposed (CONFIG_1m) there is a significant reduction of the critical stress limit parameters of the reference monopole tower increasing its static capacity. It is also obvious from the contents of Table (5) that the alternative setup (CONFIG_2m) where the 12 twelve RRUs are also moved to the tower top thus decreasing RF losses and improving the network performance, is feasible in terms of the strength criteria presented even allowing for additional margins with a relatively small increase of the total tower weight and minor translation of the center of mass. It worths mentioning here, that the deflection of the monopole tower with the REF_{mono} configuration is well outside of the 2° SLS limit. In case a strict SLS limit is required (i.e. for microwave antenna installations rather than panel type), a guided version of the monopole tower should be used instead. The option of having the newly proposed bracket significantly improves the tower serviceability, fully complying with a 2° SLS limit in CONFIG_1m and barely miss it in CONFIG_2m, even when accounting for the RRUs additional loading.

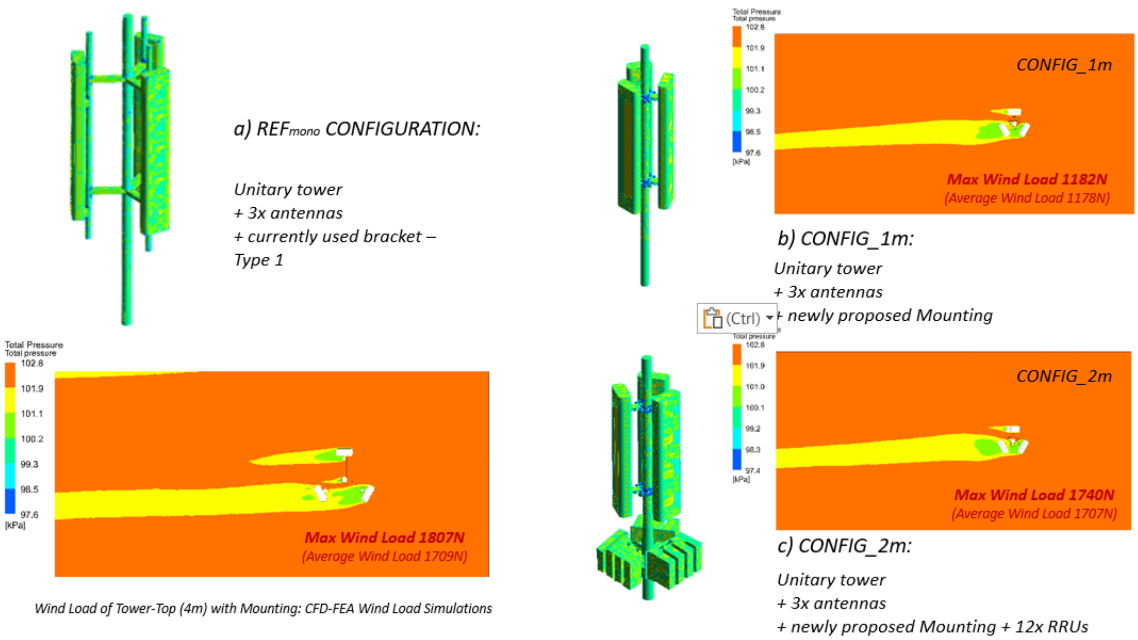


Figure (5): Wind pressure acting on monopole segment. (a) REF_{mono}, (b) CONFIG_1m, (c) CONFIG_2m.

4. Conclusion

The increasing demand for tower equipment upgrades that has been taken place due to network's modernization (to 4G, to 4G/5G, to 5G, and beyond), requiring for more and bulkier antennas to be installed at the tower tops, along with the increasing demand of tower companies to host multiple tower tenants on towers, have set multiple towers around the world to reach their static capacity limit as clearly demonstrated by Travanca et al. [7] in the case of Portugal where a 30% of the total number of telecommunications towers are considered incompatible with the reigning standards or legislation without reinforcements. This tower capacity challenge represents a key concern for both the tower companies and mobile network operators aiming at a smooth transition to 5G networks and beyond. The mobile technology ecosystem uses a solid toolkit to face this challenge (including tower equipment offloading, reinforcement, use of integrated and more aerodynamic antennas etc), spending annually billions of $ on tower redevelopment costs [37], not to mention the on-going research. The present work studies an innovative approach in the concept of tower offloading, where instead of the costly redevelopments, it focuses on an alternative solution to improve the tower's static capacity. During this work we applied this concept on representative tower cases (lattice and monopole towers), that constitute the vast majority of the global towers base (est. more than 80%), especially in developed economies that are in the forefront of 5G networks transition [38].

The present study has clearly demonstrated that offloading the antenna mounting brackets by drastically reducing their mass and surface, contributes significantly to the increase of the load carrying capacity of lattice towers and monopoles, allowing for the installation of additional equipment, equipment upgrades or simply extending the fatigue life of existing tower infrastructure (by relieving the stress condition). While the exact amount of the added benefits are case specific, adopting the presented methodology in either the design phase or during structural integrity estimation procedures is deemed important in order to maximize the capacity of telecommunication infrastructure. According to [38] the average market value per tower in Europe exceeds 320K€, taking under consideration the European tower consolidation market data from the period 2008 – 2019. Irrespectively of how big this value is, it represents a reference financial metric of the tower's capability to host revenue-making equipment, especially when assuming that the tower's remaining load carrying capacity determines future returns on investment (RoI) and immediate higher profit margins for both the tower company and mobile network operator shareholders.

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