Exploiting Wind-Turbine-Mounted Base Stations to Enhance Rural Connectivity

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The authors investigate the use of wind-turbine-mounted base stations as a cost-effective solution for regions with high wind energy potential, since it could replace or even outperform current solutions requiring additional cell towers, satellites, or aerial base stations.

Abstract

Despite global connectivity being one of the main requirements for future generations of wireless networks driven by the United Nation's Sustainable Development Goals, telecom providers are economically discouraged from investing in sparsely populated areas, such as rural and remote ones. Novel affordable and sustainable paradigms are thus indispensable to enhance the cellular infrastructure in such areas and bridge the digital divide when compared with urban ones. We investigate the use of wind-turbine-mounted base stations (WTBSs) as a cost-effective solution for regions with high wind energy potential, since it could replace or even outperform current solutions requiring additional cell towers (CTs), satellites, or aerial BSs. Indeed, conveniently installing BS equipment on wind generators would allow the transceivers to reach sufficient altitudes and easily establish line-of-sight channels within large areas. We also propose insightful simulation results for realistic case studies based on datasets for wind speed and population densities as well as wind turbines' and CTs' locations within specific Argentinian and Ethiopian exurban regions. By doing this, we hope to prove the feasibility and effectiveness of this solution and stimulate its implementation.

Introduction

Vast under-connected exurban regions lacking a reliable Internet and communication technology (ICT) infrastructure are still disseminated worldwide [1, 2]. Therefore, a primary humanitarian goal for our society is to reduce the digital gap between these regions and the more advanced ones, which are mostly urban. Achieving this goal will in turn enable many important business opportunities and technologies for rural users, but the conventional solution of deploying cell towers (CTs) inherently raises at least three important issues:

- The typical height of these structures is limited to a few tens of meters, resulting in relatively small coverage radius (a few kilometers) since the probability of establishing line-of-sight (LoS) links at larger distances becomes insufficient. This eventually leads to excessive cost, since a very capillary infrastructure is needed to cover the area of interest.
- Generally speaking, CTs' visual impact strongly disturbs rural inhabitants (note that we exclude the option of concealed CTs due to their excessive cost for a typical rural economy). Due to this, indeed, many countries worldwide have established strict regulations on their deployment.
- Since the majority of rural areas lack ubiquitous and reliable power grids, it is often necessary to install diesel generators to serve as either a main or backup energy source for the telecom infrastructure. However, diesel generators are neither sustainable nor autonomous since they produce large amounts of pollutants and require continuous fuel refilling, respectively.

Based on the aforementioned considerations, an effective alternative could be to mount base station (BS) equipment on wind turbine (WT) towers to take advantage of their tall and strong structure, which is usually already connected to the power grid and even the telecom network, for transmitting data (e.g., temperature, wind speed, humidity) to its diagnostic/control center, which in turn monitors and controls the WT itself.

The idea of providing communication functionality to WT towers was first conceived by Thomas Michael Sievert in [3], but to the best of our knowledge, it has not been implemented yet for cellular coverage enhancement. The dual solution is to mount a small WT on a CT (horizontal axis WTs have been mounted on top of or beside CTs, whereas vertical axis ones can be hosted even inside lattice structures), possibly introducing a secondary source that ensures continuous power supply. In such case, however, the height of the transceiver is still very limited, and the problem of transmitting in a LoS condition persists.

The rest of this article is organized as follows. While we first provide a brief overview of related works, the next section is an overview of the main aspects concerning the improvement of the quality of service (QoS) in rural areas. Then the proposed solution is introduced and discussed from various perspectives. The importance of the planar distributions of wind speed and population densities as well as the locations of the CTs and wind-turbine-mounted BSs (WTBSs) is discussed. Finally, we provide realistic case studies with insightful simulation results and conclude the article.

Related Works

Coverage Enhancement in Rural Areas: Recently, researchers have suggested several options to provide better services to rural users. A comprehensive overview of the most important fronthaul and backhaul paradigms for rural communications was provided in [1]. One of the most promising paradigms consists of support-

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ing terrestrial BSs (TBSs) with aerial BSs (ABSs), and its effectiveness in improving the access links was evaluated in [4]. Satellite communications systems have also gained increasing attention [5], but are usually more appropriate for very large rural regions lacking backhaul links.

Wind Energy Harvesting: In the context of energy harvesting, WTs represent one of the main pillars. Extensive overviews of the types of generators used with wind energy conversion systems (as well as the emerging technologies) have been provided in works such as [6]. The authors of [7] also discussed the networking of WTs in wind farms (WFs), but they did not consider the possibility of enhancing the QoS experienced by nearby users.

Note also that many innovative designs have been proposed for harvesting energy in more efficient and safer ways. Among them, the most promising design is probably the wind oscillator developed by the Spanish startup Vortex Bladeless. This is a vortex-induced vibration-resonant wind generator that consists of a carbon/glass fiber cylinder, fixed vertically with an elastic rod, generating electricity from its own oscillations.

Many other interesting designs have been developed for wind energy harvesting during the last decade, but few of them have been realized (e.g., the Saphonian by Saphon Energy and Invelox by SheerWind), and none of them has been commercialized on a large scale yet.

Service Enhancement in Rural Areas

Generally speaking, rural areas are strongly under-connected compared to nearby towns. The digital divide between urban and remote areas is often extreme in the least developed countries and still present everywhere. For example, the percentage of African urban households with Internet access is multiple times larger than that of its rural counterpart, whereas the difference is minor when considering any European country.

Alternative Solutions for Rural Connectivity

Several new architectures are expected to change the near future of rural connectivity. The most impactful and cost-effective might be the following ones.

Facebook Connectivity's SuperCell: This project aims to build extremely tall CTs (up to 250 m) that use 36 azimuthal sectors for higher capacity in order to reduce the total cost of the infrastructure. The field measurements mentioned in [8], in fact, reveal that the coverage area of a single SuperCell could be around 65 times larger compared to that of a conventional macro CT (30 m tall). Thus, the required density of CTs might even be reduced 20 times. This tall guyed mast, however, requires several bulky ropes for stability and hence occupies a very large area.

Altaeros' SuperTower: This is an autonomous, high-capacity, long-endurance tethered airship designed in 2019. Its optional mobile bases enable a fair amount of relocation flexibility that a drone would be able to outperform only at the price of smaller coverage radius, capacity, and autonomy. The ST-300 model can lift 300 kg of payload up to 300 m in altitude, far beyond the capabilities of tethered drones. Harsh environmental conditions still represent a key challenge for this solution as well as for any other kind of low-altitude platform (LAP).

High-Altitude Platforms (HAPs): This aerial solution consists of balloons, airships, and gliders equipped with transceivers that are mainly powered by solar energy. HAPs operate within 17–50 km in altitude, thus providing either high capacity per unit area or extremely large coverage. Although weather conditions are relatively more favorable in the stratosphere, HAPs' performance can be reduced in case of underlying dust storms.

SpaceX's Starlink: The idea behind satellite Internet is to provide global wireless coverage by means of a myriad of low Earth orbit (LEO) satellites, and Earth stations operating as relays between users and satellites. While Starlink and several other competitive projects are progressing, there are still two important concerns associated with this technology:

- Satellites can disturb astronomic observations and prevent detection of dangerous asteroids as well as discovering new planets or black holes.
- If a satellite collides with another object, it can be shattered into thousands pieces of debris, which in turn can collide with other satellites.

SpaceX partially solved the first issue by designing DarkSat (a satellite with black antireflective coatings) first and then VisorSat (which is also equipped with a sunshade). On the other hand, the second issue is considered more serious since the density of LEO satellites is rapidly increasing, and some of them are already adrift.

Sustainability and Public Opinion

Whenever a new technology is proposed, its environmental and societal impacts as well as other contextual factors must be taken into account. Herein, we briefly discuss the main concerns that governments and inhabitants express regarding the actual solutions, and we try to predict what their reaction should be to novel ones.

Regarding the public opinion on WTs' deployment, an interesting work was conducted in [9], explaining why rural communities' lack of trust in commercial developers is often a limiting factor. Deploying CTs can be even more problematic, since it is believed that they have a stronger visual impact on the landscape, and people often perceive them as more dangerous than WTs. Several television reports have also shown the negative effect of CTs on the business of a company or a household market.

The Wind-Turbine-Mounted Base Station

Proposed Designs

Different from many other renewable energy sources (RESs), large wind generators can operate almost full time during the whole year since the allowed wind speed approximately ranges from 2 to 25 m/s. Since they represent a precious resource spread worldwide in remote areas, we propose to take advantage of their robust structures to host telecom transceivers and ameliorate rural connectivity. Whenever already interconnected to the electrical infrastructure, WTBSs might also be extremely cost-effective, since they would reduce the need to deploy additional CTs, satellites, or ABSs. Mounting full BS equipment on wind generators would simply allow reaching sufficient altitudes to ensure LoS communication channels within large areas, without the need to build new structures.

Rural areas are strongly under-connected compared to nearby towns. The digital divide between urban and remote areas is often extreme in the least developed countries and still present everywhere

Having a reliable backhaul link is vital for ensuring sufficient QoS to users. Fortunately, WT towers are usually connected with optical fiber to their diagnostic/control center (or to the core network, in general). This would represent the best case for backhaul connection, although the capacity of the respective link might need to be increased for larger data traffic.

To this extent, several options can be considered:

- Given that a large WT's nacelle is approximately 3 m in height and width, and 8 m in length, resulting in a volume of 72 m^3, there often might be enough space available for mounting the BS equipment inside it so that the BS would be concealed, easily accessible, and protected from harsh weather. However, the BS transmit power should be slightly increased because of the relatively small attenuation of the signal due to the fiberglass walls of the nacelle itself. Note that telecom companies such as AT&T actually make use of fiber glass as a radio frequency (RF) transparent material to conceal BS equipment in churches or other buildings.
- If the nacelle is already full and the roof of the WT is easily accessible, the BS equipment can be mounted on top of it, so the maximum height is reached and the quality of the communication channel is optimized for the farthest users.
- If the nacelle is already full and the roof of the WT is not easily accessible, the BS equipment can be mounted along the tower itself, beneath the hub. In this case, the telecom equipment would be completely independent of the WT components, but the coverage radius would be smaller compared to the previous options. Moreover, if the transceivers are installed at an altitude below the area spanned by the blades, any possible interference (due to scattering or reflection) caused by the latter would be avoided.

Evidently, the first case requires the energy and the telecom operators to share the same room, while for the second and especially the third case they would be more independent of each other. Note that analogous considerations can be done for novel designs such as the Saphonian wind generator mentioned earlier if its size is increased to be comparable to large WTs. However, the higher mobility of its nacelle should be taken into account. For the case of wind oscillators such as Vortex Bladeless, instead, the most convenient option might be to install the transceivers on top of the structure, although the effect of its oscillations should be investigated.

Backhaul Solutions

Having a reliable backhaul link is vital for ensuring sufficient QoS to users. Fortunately, WT towers are usually connected with optical fiber to their diagnostic/control center (or to the core network in general). This would represent the best case for backhaul connection, although the capacity of the respective link might need to be increased for larger data traffic. Wherever optical fiber is not already available (this usually happens because it is not economically convenient to dig channels to lay several kilometers of optical fiber underground), and if the WT is connected to the grid, it might be possible to wrap the optical fiber around overhead power lines by means of Facebook's connectivity robot, Bombyx, or alternatively rely on point-to-point (P2P) backhaul by means of microwave channels since the nacelles are usually made of RF-transparent materials such as glass fiber-reinforced plastic (GFRP).

Another interesting option could be to possibly take advantage of the deployment of LEO satellites. Indeed, it might be convenient to install a satellite dish on top of the nacelle of the tallest WT of a WF and use it to connect the other ones in a star-fashion by using millimeter-wave (mmWave) or television white space (TVWS) unlicensed spectrum links. Again, nearby rural users could access the Internet by associating with the BSs attached to any of the equipped WTs.

Energy-Related Considerations

The power consumption of the BS equipment is usually negligible compared to the power produced by a large WT. Typical BS equipment requires about 5–10 kW, of which around two-thirds is due to the RF equipment, and the remaining third is due to the air conditioning system, the digital signal processor, and the AC/DC converter. Assuming a grid-connected WT, the optimal choice is usually to connect the BS equipment directly to the grid in order to minimize the risk of interrupting telecom services. For standalone WTs, instead, a backup source connected to the direct current (DC) link of the WT's inverter (e.g., a battery pack, a fuel cell system, or a diesel generator) would be needed to ensure continuous service, but this would probably require placing it outside the tower since the available space inside is quite limited. Another important aspect is the possibility of consuming green energy directly from the source, since the latter can considerably reduce both the cost and the environmental impact of any energy-intensive application. A noteworthy example is WindCORES, a collaboration between Fujitsu's Green IT initiative and WestfalenWIND IT aiming to take advantage of the space available at the base of WT towers to host sustainable data centers at competitive prices.

Economic Aspects

When talking about rural connectivity, the largest percentage of the total cost derives from building both the power and telecom infrastructures. While many sparsely populated areas do not have access to any of them, some others can enjoy the availability of a power grid. However, BSs need a reliable power supply in order to function continuously over years; thus, both the capital expenditures (CAPEX) and the operating expenditures (OPEX) may become excessive.

The proposed solution expects to drastically reduce the cost of these infrastructures by simply avoiding building CTs and, in some cases, even digging optical fiber cables. In fact, if the WT is already connected to the core network, the existing link could also support additional mobile users or devices for Internet of Things (IoT) applications. By means of their financial support, telecom providers might also be key enablers for deploying new WTBSs and reducing the carbon footprint of the telecom industry. This is why several companies, including AT&T, have started relying more and more on WTs and other renewable energy sources for powering their own infrastructures, also taking advantage of considerable government subsidies. For existing WTs, other kinds of agreements such as simple rent for hosting the BS equipment should be considered by power and telecom providers.

Finally, we also highlight that the proposed solution should not require any additional permission from the public authorities and hence could be implemented in a much shorter time compared to the conventional ones.

Planar Distributions

When evaluating the possibility of deploying WTBSs, very accurate planning should consider the average distance between the tower and the interface with the power grid, since the BS equipment is preferably connected to the latter. However, the three main entities that should be preliminarily taken into account are population, existing CTs, and existing WTs. In this section we discuss the required features for the planar density distributions of these entities over the environment considered.

Population maps need to be analyzed carefully in order to understand whether the site is appropriate for equipping WT towers or not. Evidently, if there is a scarce density of users, the cost of providing cellular coverage might not be justified unless unmanned applications such as industrial IoT and precision farming are needed. A minimum distance of a few hundred meters (mainly depending on the level of urbanization and the size of the WT) between any WT and any inhabited center also should be considered to meet government regulations and avoid disturbing nearby residents.

Regarding existing BSs, if their density is already high within the considered area, it might not be useful to increase their number by equipping any WT towers, although this case is very rare in rural areas. In other words, mounting transceivers on WTs would be most effective when there is a low density of CTs and a large density of users.

Although this solution is also applicable to new WT towers, its economic effectiveness should be maximized by taking advantage of existing structures. Trivially, the more WT towers are already available, the more choices we have about which of them should be equipped to maximize networks' performance. Note that countries such as Denmark already have an average density of onshore WTs that is theoretically enough to cover all of their rural communities, even without the support of existing CTs.

Proof of Concept

This section provides interesting simulation results showing the performance enhancements that proper deployments of WTBSs could bring to existing networks.

Since 5G CTs are not available yet in the considered exurban areas [10], we assume WTBSs to operate as 4G BSs. Furthermore, given that the datasets in [11] refer to the locations of the center of the WFs, we will assume to mount at most one BS equipment per WF, which will also minimize the interference due to clustered BSs as well as the costs of WTBSs' deployment.

Channel Model

Our system model conceives six possible types of communication links, depending on the structure hosting the BS (CT T or WTBS W), the mobile technology (3G or 4G for CTs, 4G for WTBSs) and the type of transmission (LoS L or non-LoS [NLoS] N) with respect to the user. Let the subscript $Q \in \{TL3, TN3, TL4, TN4, WL4, WN4\}$ denote the type of BS, with the first letter referring to the structure, the second one to the type of transmission, and the number denoting the generation of mobile technology. We assume that each wireless link between the user and BS Y_i experiences small-scale fading in the form of Nakagami-m distribution with its specific shape parameter m_Q and channel fading power gain G_{Q,Y_i} following a Gamma distribution. We also introduce the mean additional losses η_Qs and the transmit powers p_T and p_W and consider a standard power-law path loss model characterized by the path loss exponents α_Qs.

Note that NLoS and LoS transmissions occur with specific probabilities depending on the height and density of the buildings, the type of environment, and the elevation angle. Indeed, according to [12], the LoS probability is a function that depends on two environmental constants, called s-curve parameters ($\mathcal{S}_a$ and $\mathcal{S}_b$), and increases as the elevation angle of the BS increases. Trivially, the NLoS probability is complementary to the LoS one, and each BS is assumed to be in either LoS or NLoS condition with the user, independent of the other BSs. Finally note that, for the sake of simplicity, we neglect antenna gains and assume that all the BSs are omnidirectional.

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Data Rate

We adopt the strongest average received power association policy; therefore, the user connects to the BS providing the highest average received power. However, in order to maximize the average data rate per user, we penalize the association to 3G BSs by introducing a bias factor on the power that would be received in case of association to a 4G BS. The instantaneous signal-to-interference-plus-noise ratio (SINR) will be the ratio between such received power from the serving BS and the sum of the aggregate interference (sum of the received powers from all the other BSs) and the additive white Gaussian noise (AWGN) power σ_n^2. The coverage probability is defined as the probability that the SINR exceeds a designated threshold β, which leads to introducing the lower bound $\bar{R}$ of the average data rate as the product between the coverage probability and the data rate R_Q^* that a specific BS can provide when the SINR is exactly equal to β. Note that the average data rate is here intended by referring to the geographical sub-areas rather than the users located within any specific cell.

Case Studies

This part of the article discusses different realistic environments where WTBSs could be conveniently deployed based on the simulation results we have obtained. The first type of environment we propose is a rural area in a low-income country such as Ethiopia, where both the telecom and WT industries are very limited but rapidly growing. The second type instead identifies an exurban environment in a windy area of Argentina, where fewer WFs are available, but there is a higher potential of power generation as well as a larger population needing connectivity. For both cases, having considered the average wind speed density, we adopt useful open source datasets for population density [13] and the locations of both CTs [10] and WTs [11].

All the simulations have been performed by considering the following system parameters: α_L = 2.2 and m_L = 2 for LoS transmission, α_N = 3.2 and m_N = 1 for NLoS transmission, β = –5 dB, σ_n^2 = 10^{-12}, W/Hz, p_T = 10 W, and h_T = 30 m for CTs, and p_W = 11 W and h_W = 100 m for WTBSs. We model the Ethiopian case study as a rural environment and the Argentinian one as a suburban environment according to [12]. Therefore, we set:

- η_3 = –0.1 dB and η_4 = –21 dB for 3G and 4G BSs, respectively, $\mathcal{S}_a$ = 4.88, and $\mathcal{S}_b$ = 0.429 for rural areas.
- η_3 = –1dB, η_4= –20dB, $\mathcal{S}_a$ = 9.6117, and $\mathcal{S}_b$ = 0.1581 when considering suburban environments.

Having assumed R_3^* = 2 Mb/s and R_4^* = 17.5 Mb/s for 3G and 4G BSs, respectively, and biasing the association, all the simulation results have been averaged out over 10^4 iterations, since the LoS or NLoS condition is a random variable.

Central Ethiopia: Ethiopia is probably the most promising African country for future installations of WFs. Moreover, this country needs to drastically reduce its imbalance index for telecom services [2] in order to improve its economy, since almost its entire population cannot access 4G services.

The area of interest equals roughly 4400 km^2 and hosts more than 91,000 inhabitants. As displayed in Fig. 1, this region is less than 100 km^2 far from the capital and is still totally lacking 4G CTs [10].

Given the current presence of two WFs [11], we propose to install an additional WTBS to cover the northeast corner of the area, which in general leads to a noticeable increase of $\bar{R}$, as confirmed by Fig. 2. Starting from 2.88 Mb/s, the average data rate per user has also been ameliorated by approximately 12 percent.

Southern Argentina: The huge wind potential of this region was partially exploited only a few years ago. However, Argentina's installed capacity of WTs almost tripled from 2018 to 2019 [11], meaning that there is now strong interest in this technology.

We have chosen a simulation area with approximately 27,000 inhabitants distributed over 20 km^2 in the western periphery of Comodoro Rivadavia. This zone is characterized by a poor telecom infrastructure, according to [10]. Since this town is gradually converting its power sources from oil to wind (the average speed is approximately 9.75 m/s [14]), we propose to deploy new WTBSs in some strategic locations, as illustrated in Fig. 3.

Having optimized the bias factor to a value of 22, the simulation results clearly show an overall improvement in terms of the average data rate available for the mobile users residing in this area. Indeed, it can be inferred from the heat maps in Fig. 4 that the number of proposed installations is sufficient to cover the entire area of interest. Trivially, the zones with the highest average data rate are located in the proximity of the WTBSs, since they provide 4G connectivity and easily establish LoS links within distances of several hundred meters. Note also that the areas far from any of these hybrid structures are not considerably affected by a significant increase in the inter-

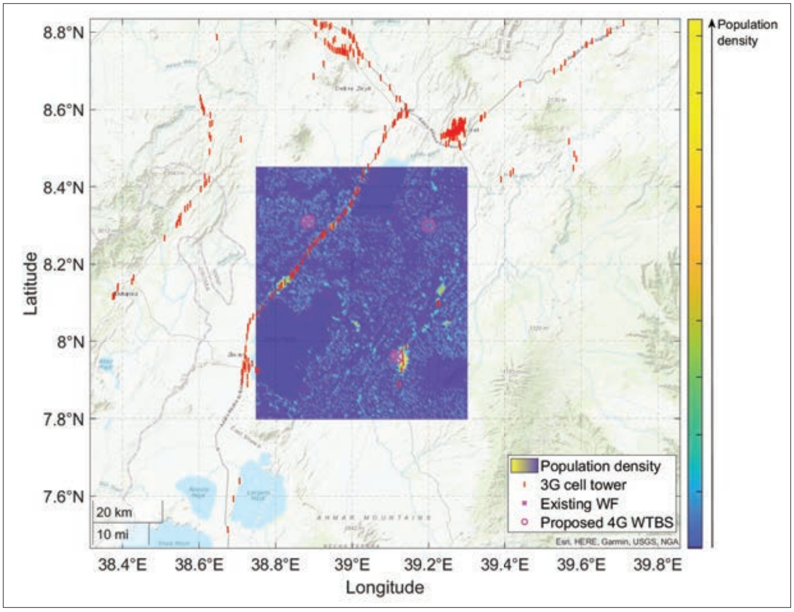

FIGURE 1. System setup for the case study in central Ethiopia.

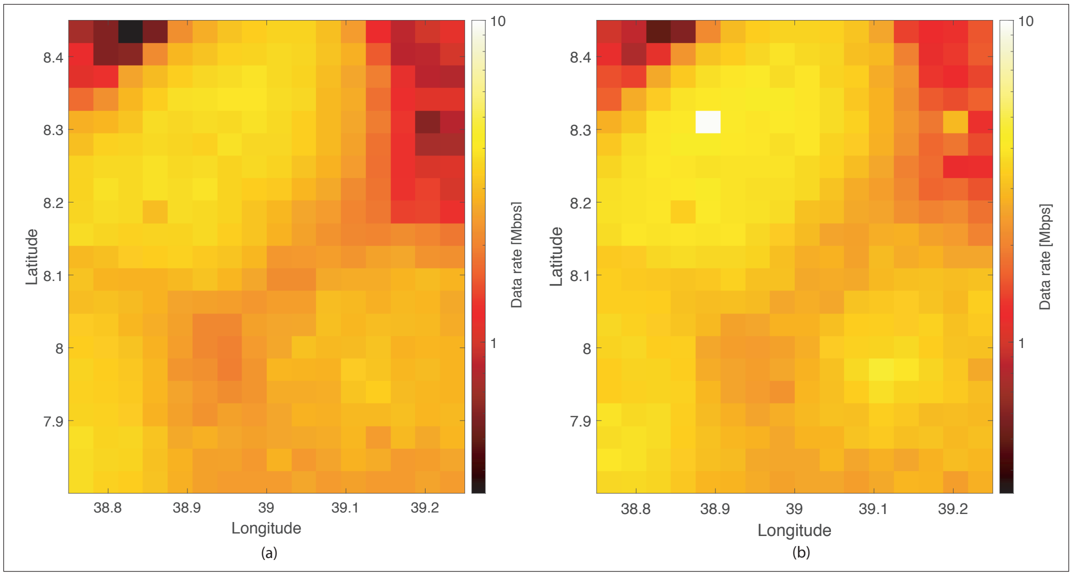

FIGURE 2. Data rate distributions in the central Ethiopia case study when: a) no WTBSs are deployed; b) the proposed WTBSs are deployed.

ference. Normalizing on the population density, the average data rate has been enhanced from 3.54Mb/s to 4.13Mb/s.

Upcoming Wind Energy-Based Projects: Although the Kingdom of Saudi Arabia (KSA) still almost solely relies on oil as an energy source, the city of NEOM is an ambitious project that expects to be fully powered by renewable energies. According to the official website, wind and solar energies will also be used to produce green hydrogen, which can be better stored. Several works have promoted the high wind potential of this region, which is characterized by high-speed and slightly variable winds over the whole year. A thorough case study has been conducted in [15], where a WF made of 100 identical WTs (each one with rated power of 3.2 MW) has been proved to be profitable even without any government subsidy. WTBSs would thus be an effective solution for limiting the visual impact on NEOM's landscape, especially given its goal of preserving 95 percent of its natural resources (note also that off-shore WTs have a positive impact on sea life).

Another interesting project regards Denmark's largest construction ever, an energy island that is expected to produce up to 10 GW mainly using off-shore WTs. Evidently, the cost of the telecom infrastructure would be much higher in such a remote environment, apart from the fact that there is a very limited surface available. Thus, off-shore WTs could be the perfect structures for hosting BS equipment, since they are bigger and stronger than their on-shore counterparts.

Conclusions and Future Work

By means of realistic case studies, we have shown that deploying WTBSs can be an effective solution for improving average data rate in various types of environments worldwide. Therefore, we believe that WTs should be further incentivized in underdeveloped countries and rural areas in general.

An open problem might be numerically optimizing the number and locations of WTBSs. Future works should focus on the integration of this technology in a more complex network that also includes ABSs, LEO satellites, and aerial users (e.g., delivery drones or flying cars), for instance. Finally, the feasibility of mounting the BS equipment should also be evaluated for innovative and promising wind energy harvesting structures, such as bladeless wind oscillators, that aim to avoid problems of signal scattering or reflection due to the blades, and minimizing acoustic pollution and bird death.

References

[1] E. Yaacoub and M.-S. Alouini, "A Key 6G Challenge and Opportunity — Connecting the Base of the Pyramid: A Survey on Rural Connectivity," *Proc. IEEE*, vol. 108, no. 4, 2020, pp. 533–82.

[2] C. Zhang *et al.*, "On Telecommunication Service Imbalance and Infrastructure Resource Deployment," 2021; https://arxiv.org/pdf/2104.03948.pdf.

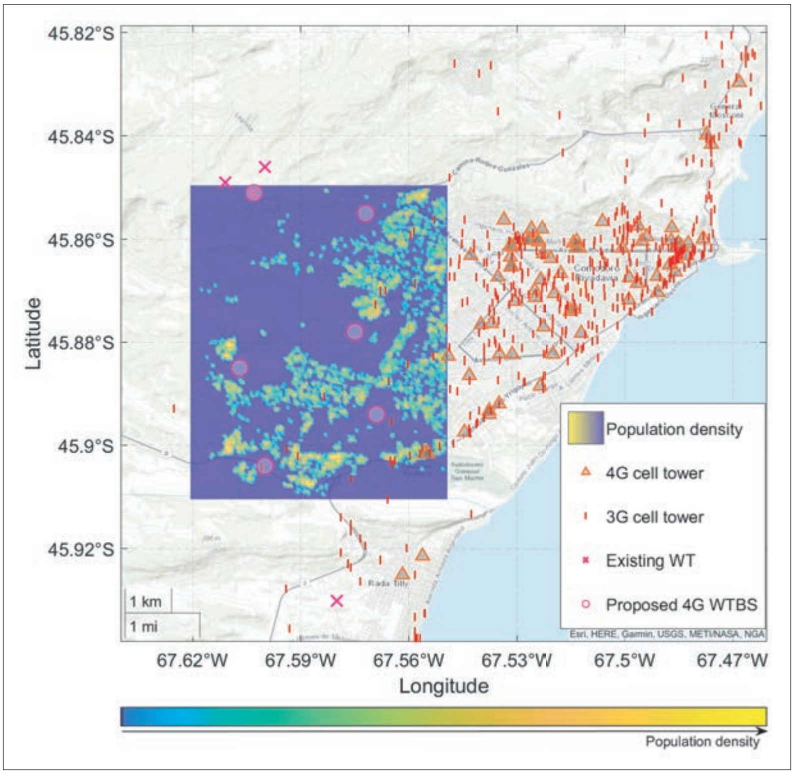

FIGURE 3. System setup for the case study in southern Argentina.

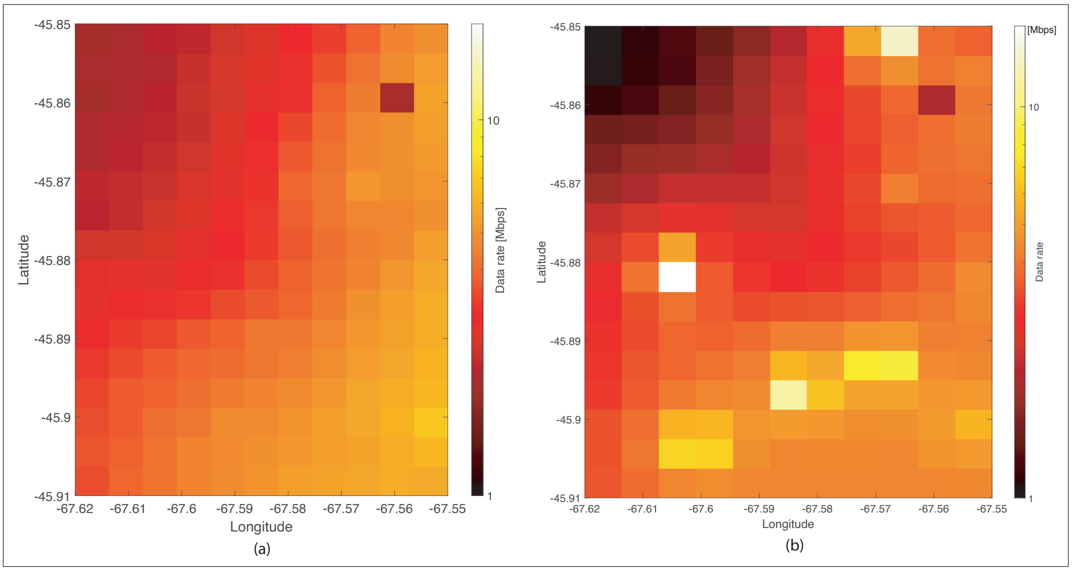

FIGURE 4. Data rate distributions in the southern Argentina case study when: a) no WTBSs are deployed; b) the proposed 4G WTBSs are deployed.

[3] T. M. Sievert, “Modification of Wind Turbines to Contain Communication Signal Functionality, by Nov. 21, 2006,” Patent US 7,138,961 B2; https://patents.google.com/patent/US20040232703A1/en.
[4] M. Matracia, M. Kishk, and M.-S. Alouini, “Coverage Analysis for UAV-Assisted Cellular Networks in Rural Areas,” *IEEE Open J. Vehic. Tech.*, vol. 2, 2021, pp. 194–206.
[5] A. Talgat, M. A. Kishk, and M.-S. Alouini, “Stochastic Geometry-Based Analysis of LEO Satellite Communication Systems,” *IEEE Commun. Lett.*, 2020.
[6] Devashish *et al.*, “A Review on Wind Energy Conversion System and Enabling Technology,” *Int’l. Conf. Electrical Power and Energy Systems*, 2016, pp. 527–32.
[7] M. A. Ahmed and Y.-C. Kim, “Communication Network Architectures for Smart-Wind Power Farms,” *Energies*, vol. vol. 7, 06 2014, pp. 3900–21.
[8] A. Tiwari, “SuperCell: Reaching New Heights for Wider Connectivity,” 2020, Facebook Engineering; https://engineering.fb.com/2020/12/03/connectivity/supercellreaching-new-heights-for-wider-connectivity/.
[9] M. Leiren *et al.*, “Community Acceptance of Wind Energy Developments: Experience from Wind Energy Scarce Regions in Europe,” *Sustainability*, vol. 12, 2020, p. 1754.
[10] U. labs, “cell towers.csv.gz”; https://www.opencellid.org/downloads.php, accessed Dec. 8, 2020.
[11] The Wind Power, “Windfarms Argentina 20210211.csv” and “Windfarms Africa 20210730.csv”; https://www.thewindpower.net/store windfarms view all en.php, accessed Aug. 12, 2021.
[12] A. Al-Hourani, S. Kandeepan, and S. Lardner, “Optimal LAP Altitude for Maximum Coverage,” *IEEE Wireless Commun. Lett.*, vol. 3, no. 6, 2014, pp. 569–72.
[13] Humanitarian Data Exchange (HDX), “population eth 2018 10-01.csv.zip” and “population arg 2018-10-01.csv.zip”; https://data.humdata.org/search?groups=eth&groups=arg&q=population%20density, accessed Nov. 4, 2020.
[14] Department of Wind Energy at the Technical University of Denmark, and World Bank Group, ”Global Wind Atlas (GWA 3.0)”; https://globalwindatlas.info/, accessed Mar. 4, 2021.
[15] F. Alfawzan, J. E. Alleman, and C. R. Rehmann, “Wind Energy Assessment for NEOM City, Saudi Arabia,” *Energy Science & Engineering*, vol. 8, 2020, pp. 755–67.

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