Instituto Tecnológico y de Estudios Superiores de Monterrey

Campus Monterrey

School of Engineering and Sciences

Mobile Coverage Solutions for Not-Spots in Rural Zones of Latin America

A thesis presented by

Diego Fernando Cabrera Castellanos

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Dedication

Firstly, this study is wholeheartedly dedicated to God: You have caught me with your magnificent love during the last years. I would like to recognize your great support and your countless blessings in my growth as a loyal and straightforward person.
(Mathew 19:26, Psalm 73:25-26)

In a second place, to my entire family but especially to my beloved grandmother Yolanda, since she has been noticeable evidence of the faithful and sincere love despite the lacks or the drawbacks during her life's walking. Her struggle is and will be my source of inspiration.

Finally, to my dear country Colombia, because at the time I ended this book, my co-nationals have been striving to gain a fair nation to the upcoming generations.

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Abstract

The access to broadband communications in different parts of the world has become a priority for some governments and regulation authorities around the world in recent years. Building new digital roads and pursuing a connected society includes looking for easier access to the Internet. In general, not all the areas where people congregate are fully covered, especially in rural zones, thus restricting the access to data communications and therefore bringing inequality. In rural areas, there are multiple challenges to deliver reliable communication, such as a suitable roll-out of IoT structures and introducing the ubiquitous network model in the countryside.

Accordingly, the use of three platforms to deliver broadband services to such remote and low income areas were studied: Unmanned Aerial Vehicles (UAV), Altitude Platforms (APS), and Low-Earth Orbit (LEO) satellites. On the other hand, the use of terrestrial networks—such as optical fiber centered—seems suitable but non-affordable because of the rural orography's high complexity. The analysis of terrestrials deployments is out of the proposal scope. Hence UAV were considered a noteworthy solution to be assessed in the experimental stage—by using the algorithm performed through electronic processors—since its efficient manoeuvrability can encompass the rural coverage issues of not-spots.

To support the primary aim of analyzing the viability of deploying alternative BSs based on UAVs, the obtained results indicated that there are manifold shortcomings in the stated model due to the limitations on the accuracy of the used devices besides the bounded number collected information. Nevertheless, this approach can become an outstanding opportunity to develop the AGC research by considering higher-level simulations and even trustworthy LTE deployments to spur a fully connected countryside in Latin America and the entire world.

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Chapter 1

Introduction

Coverage indicators are essential to perceive the reliability of the network in a determined area. Specifically, each country defines the best practices to determine the covered zones for their boundaries and, therefore, the appropriated thresholds associated with frequency bands. Commonly, most mobile operators offer coverage on the main urban area [59], limiting the countryside to lower bandwidth, thus reducing connection speeds [83]. Nevertheless, the interest in providing more connectivity in rural zones has grown in the last decade since the economic development will be the immediate fact.

A huge terminology has arisen to address the coverage holes, wherein a few or even any operator guarantee its services. The Ofcom—Office of Communication of the United Kingdom—nominating them as *Not-Spots*. The prior entity has the intention to reach the coverage index until 95% by 2022 [80]. Several British operators (O_2, Vodafone, EE, and Three) have implemented a sharing strategy, allowing a mutual infrastructure approach to improve competition in the countryside. This layout—or National Roaming—shall grant to customers in rural areas the possibility for connection to the strongest available signal, regardless of the chosen operator for these clients [80].

The inequality to access to Information and Communications Technologies (ICT) resources and the lack of opportunities to reach development are the most significant drawbacks in developing countries, even though the mobile devices accounted for 87% of broadband connections there [56]. Latin America is not so far from that situation. However, most governments have changed the way to support more connectivity opportunities in the last decade.

Within the call for promoting a prosperous society, which can curb inequality and poverty, the United Nations (UN) has considered the access to fixed-broadband Internet—under the Goal 9 outline: Industry, Innovation, and Infrastructure—a valuable resource to population's growth. By 2018, 96.5% of the entire world population can access at least 2G mobile networks where LTE covers 81.8% of the [91]. In full swing of the Internet Era, not all the villages are able to leverage granted-by-connectivity opportunities because of the highest cost of access, unearthing the at-risk population group's unfairness.

With the ongoing demands of communication infrastructure, the UN Sustainable Goal 9 aims to significantly increase ICT resources access by 2020, besides struggling to hook up LDC (Least Developed Countries) with affordable technology [76]. The COVID-19 pandemic has triggered comprehensive research and investment in digitalization, namely economy and education boosting, since teleworking, video conferencing systems, and remote education have been crucial parts of in-pandemic and post-pandemic times.

1.1 Motivation

To figure out the connectivity situation around the world, the GSM Association (GSMA) provides the GSMA Mobile Connectivity Index (MCI)—the current is by 2019—which measures the performance of 170 countries, based on four key enablers of mobile internet adoption: infrastructure, affordability, consumer readiness, and content and services [52]. The prior institution has released *The State of Mobile Internet Connectivity 2020 Report*, which analyses the critical connectivity trends from 2014 to 2019 in terms of mobile internet use [56].

The coverage has not been widely enough to provide the same standards compared to Europe. For instance, in [56] is possible to check that Europe and Central Asia and North America own more of 70% connected than the 54% of Latin America & Caribbean. Despite this, it is crucial to stand out about the services offered has grown in the last region, since its MCI overcomes a 61 score by 2019, in contrast with the obtained five years earlier: 51 [52].

Although the MCI appears to be the most significant, this is not the only affair to highlight at the moment to analyze the connectivity for particular contexts, like the countryside. Therefore, it is necessary to map out the earlier metric with each country's rural population density, discovering the most important limitations that prevent people from adopting mobile internet. Table 1.1 depicts both MCI and *Rural Population Density* (RPD)—in percentage units from the total—to analyze the gap among fifteen Latin countries themselves.

Table 1.1: Contrast between MCI and RPD of 15 Latin America Countries [52]

Country	MCI	RPD
Argentina	67.2	8
Bahamas	68.7	17
Brazil	63.5	13
Chile	73.2	12
Colombia	63.7	19
Costa Rica	63.3	20
Dominican Republic	59.8	18
Ecuador	65.3	36
El Salvador	55.4	27
Haiti	32.8	44
Mexico	67.6	20
Panama	65.3	32
Peru	66.6	22
Uruguay	76.7	5
Venezuela	57.4	12

1.2 Problem Statement and Context

To address the unconnected panorama into a specific case, Mexico and Colombia will be suitable study cases to in-depth analyze the deployment based on alternative network—besides of the current wireless form of communication—since the statistics exhibit the endurance of MNO to grant the connectivity in both urban and rural settlements but for the last particularly. For instance, The Mexican Institute of Statistic and Geography (INEGI) points out in [50] that there is only 56.4% of fully connected households in 2019, contrasted with the 39.2% in 2015. Although the coverage gap has shrinkage in the last five years, there are no boundless possibilities to bestow the in-full-swing coverage.

Considering the aforementioned specific cases in the region, identifying the locations in which the coverage is under specific boundaries appears to be suitable to sketch out the Not-Spots presence in these contexts. Therefore, Figure 1.1 charts the correlation between the total population and the coverage density, segregated by the mobile networks' generation, from 2G to novel 5G. This purpose aims to recognize the coverage gap inside the mentioned countries. Besides, it likely identifies regions whose population can not access nor Voice nor Data services.

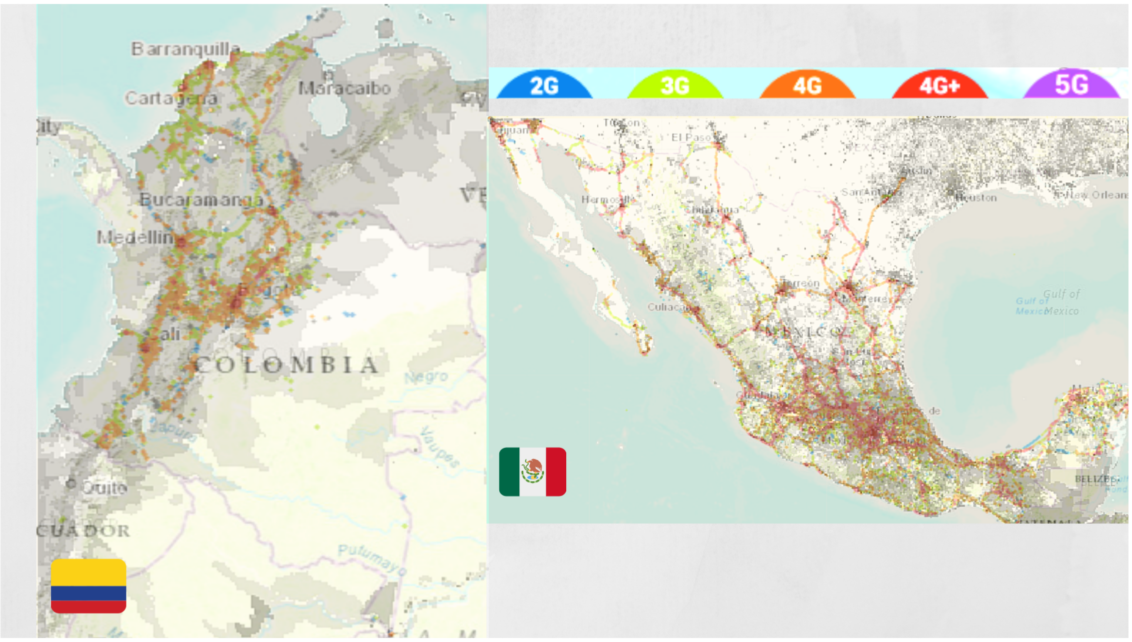
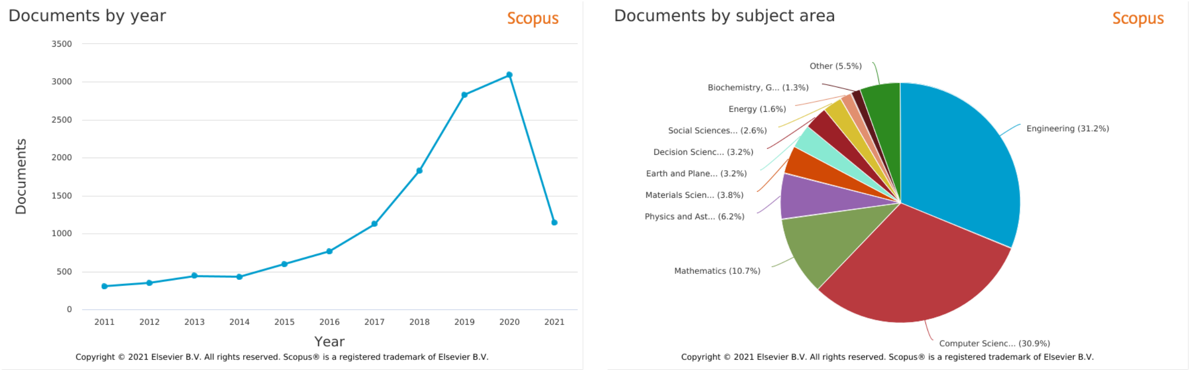


Figure 1.1: Correlation between Population and Current Mobile Networks Coverage in both study cases

1.3 Research Question

Since Information Technologies and Communications (ICTs) have incurred several countries' social development and economic growth, they have been worthy of getting closer to novel approaches, such as the Internet of Things (IoT) and 5G. Even though this scope is not wholly reachable in the stated study countries—Mexico and Colombia—these entities strive for strategies that allow connectivity in the countryside and boost the economy's primary sector, agricultural and raw material industry.

By envisioning a proper solution to improve the coverage in those rural zones, the *foremost aim* is to analyze the viability of deploying alternative BSs based on LAPS, such as UAVs. The physical device prototype should be easy to roll out, tractable, affordable, and far-reaching to identify the countryside's network parameters as long as the coverage would initially enhance the low-income and inaccessible zones of Latin American communities.



(a) UAV-based Communications Trend by Year (b) UAV-based Communications Trend by Subject

Figure 1.2: Impact Analysis of the Thesis Scope

UAV-based communications have become a tendency in the last decade. This scope can support the hypothesis—mentioned in the prior paragraph—aside from encouraging the new research field to involve new forms of communications, boosted by the novel technologies as MTC, IoT, and 5G. Beforehand establishing the primary approach of the current thesis project, it was relevant to in-depth seek the potential UAV role—besides others LAP/HAPs—in communications subject. Therefore Figure 1.2 states its investigation production during the last decade, retrieved from Scopus database.

On the other hand, there are the insights of the investigation, namely its specific objectives, which approach the hypothesis and stand out the methodology's basis. The following targets address the scope of the research:

- Realize a thorough characterization of rural communities—in both study cases—to identify the central claims tackling ICT issues.
- Perform an experimental test of the prototype to determine the viability and firmness of the proposed device, thus generating models that fit the settlement requirements.
- Set forth the role of the connectivity in the social development and economic growth of the countryside populations after realizing the advantages of bestowing a reliable network infrastructure to promote the rural evolution, especially in the post-pandemic era.

1.4 Solution Overview

To obtain solid results and assess the coverage improvement by deploying the suggested novel rural network infrastructure, developing the model device deserves a broader investigation. Figure 1.3 illustrates the block diagram of the foremost steps that were performed in the current process. In a nutshell, the model requires formal research to test the scope of the hypothesis. The aforementioned Figure sets forth the primary facts of each process and states the outcomes that will be the cornerstone of the final prototype.

The COVID-19 pandemic was challenging for the *Deployment* stage because the obtained measures to support the *Simulation* process were no sufficient to establish an accurate

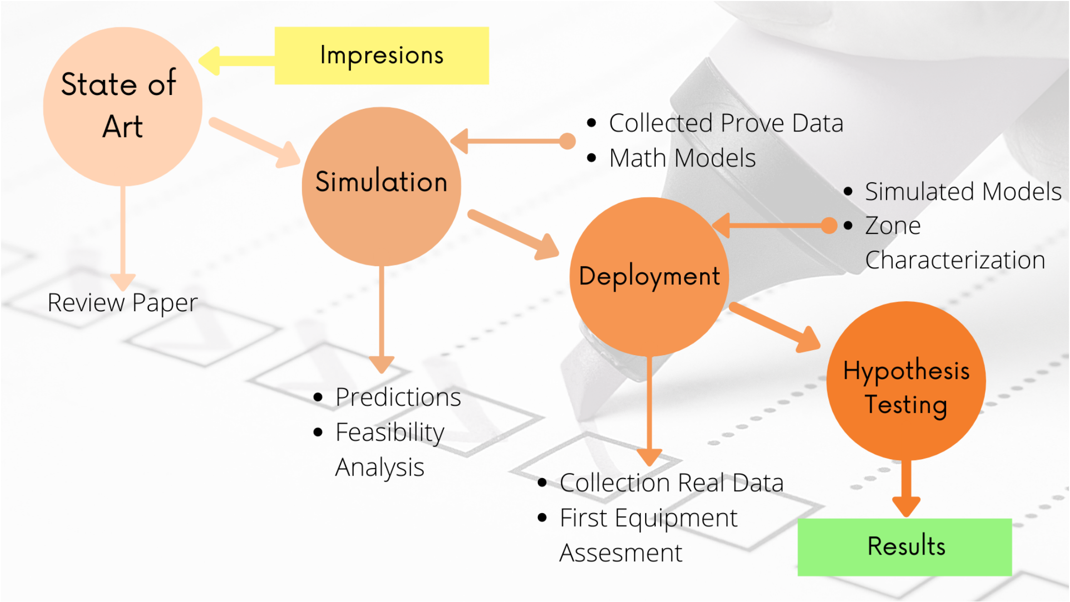


Figure 1.3: Proposed Methodology to Achieve the Research Question

but straightforward model. Despite this fact, several measures were taken in a rural community—in Manizales, Colombia—to fuel the overall process and guarantee the hypothesis testing stage, and expecting for a prototype of connectivity that improve the coverage index in the rural zones. Consequently, the simulations top off with LTE receiver design and then sketching out the feasibility of unfolding UAV-based BS to approach the goal of the research.

1.5 Main Contribution

The proposal arises to determine the feasibility of the rural coverage improvement and, therefore, tackling both *outdoor* and *indoor* not-spots in the mobile networks. Underneath a reliable connectivity aim in the Latin countryside, new approaches will be addressed to enhance the current services offered by the MNOs and introducing new standards for the full-disconnected communities, such as the stated ones in Figure 1.4, which are IoT for agriculture, remote medicine and education and rural framework for 5G rollout.

This proposal is based on descriptive research since it is imperative to provide an appropriate validation of the current conditions regarding signal quality in the countryside, considering the specific cases of Mexico and Colombia (zone characterization). Then, executing research from the obtained data will be essential to decide the suitable solution for the raised hypothesis. This inquiry might lead to designing an optimal network infrastructure that solves the coverage issues in rural zones and accomplishes strategically and economically developed regions.

Figure 1.4: Proposed Methodology to Achieve the Research Question

1.6 Disertation Organization

In the following sections, the development of the validation of the proposed aim will be accomplished as long as the methodology—displayed in Figure 1.3—leverage the stages issues to achieve the UAV-centred prototype. Besides realizing the emerged challenges during the entire process—mainly driven by the COVID-19 pandemic lockdowns—this book is organized as listed below.

Chapter 2 presents the state-of-the-art of rural communication, evaluating the role of SCP as the most suitable solution to the countryside's weak connectivity. Chapter 3 dive into the methodology plan besides sketching out the used material that accomplishes with the scope. Chapter 4 undertakes the obtained result in both the simulation and deployment stage. Finally, Chapter 5 states the discussion about the bestowed solution for the rural not-spots. The used algorithms to reap the results and outcomes in the entire process are addressed in the Appendices A, B, and C besides a summarize of the used acronyms in the book.

Chapter 2

The State-of-Art

2.1 The Rural Paradigm Shift

Under the perspective to grant better connectivity standards in the countryside, it is adequate to set forth the differences among several best-fitted technologies to find an optimal solution. The first approach is a suitable onset to focus on including mobile network connection optimizing for rural populations and self-steady links for IoT terminals, whether involving the new communication tendencies, such as Device-to-Device communications (D2D) or even 5G [55].

Outdoor and indoor environments require the above aims to lift specific responses within the rural population needs. The outdoor schemes consider current traffic estimation of the mobile network by algorithmic focusing since it may provide the proper breakdown to determine the cells coverage capacity [34]. About indoor environments, achieving an extended coverage based on Ad-Hoc Networks by lower frequency bands involving repeaters [86] would be suitable. The subsections 2.1.1 and 2.1.2 will cope with the solutions for both cases.

2.1.1 Outdoor Perspective

Gatwaza et al. in [34] highlighted that traffic is an outstanding factor in network dimensioning. In isolated zones, the challenge lies in finding out how to fix the maximum coverage per single base station by the complex topography, and the highly dispersed population distribution [27]. Information of geographical distribution is quite relevant for Internet Service Providers (ISP) since it allows the estimation of the areas that deserve specialized deployment toward determining the under-requirements system capacity [30].

The coverage parameter defines the network scope, leading to the expected enhance for lower-connectivity regions. Consequently, the measurement of propagation parameters, such as Path Loss Exponent and Losses, are essential for coverage and quality analysis. For instance, CDMA and AMPS cells may overlay the target geographical areas to appropriately carry the information among the remote Base Stations (BS) [33]. Other alternatives include the use of WiMAX—IEEE 802.16—set of standards [64] and the TV White Spaces (TVWS) [13] to enable a ubiquitous network.

At the onset of century XX, development countries evaluated options to achieve better

Figure 2.1: Some Solutions for Outdoor Networks Issues

QoS in rural zones. One of them was implementing high-quality-in-car mobile services without the implementation of new cell sites. Thus there was a possibility to raise the roadways coverage area through antenna arrays set over constant on-ways cars. This advance might have allowed minimizing cost surround no installation of more BSs. Furthermore, it would give steps forwards due to implementation over that dynamic CDMA signals, eradicating AMPS services [33].

With the massification of novel technologies, e.g. 5G and IoT, for urban zones, the idea includes analyzing other kinds of low-deployment cost options, such as FTTx. Araujo, Ekenberg, and Confraria point out in [16] that services on FTTC (Curb) would be 70% cheaper than 5G implementation and 20% less expensive than FTTH (Home). Although the main idea is boosting the countrysides as high-opportunities potential zones, non all operators expect to invest in high-cost infrastructure for low-dense populations because its rollout may cost 80% higher than in urban zones [85].

So far, several approaches have arisen regarding reach the desired coverage index. Knowing that 5G services are not considered for the countryside yet, IoT services are limited in terms of high-reliable networks. More quantity of unfolded BSs, more coverage index may be reached, increasing the efficiency [16]. The BS coverage area is more significant than 0.5 km, and having enough overlapped-with-adjacent cells will ensure the quality of roaming at the maximum allowable distance among them [96].

In mobile networks, the handover parameter is triggered when a User Equipment (UE) detects a better signal strength of the neighbouring cells [59], but it can also regard the non-convergence in the case of rural zones. Thus, identifying the BS coverage area at network planning is a relevant part of the design process. The 3G services may be the first technology to implement in the countryside since it is possible to monitor the network parameters —as coverage and cell capacity—by desiring appropriate Signal-to-Noise rates (SNR) and QoS index. It is important to recall that the rural connectivity gap is proportionally greater for low-income households [84].

After reviewing some references, we found that *Stratospheric Communication Platforms* (SPC) have been trending in the last decade for outdoor solutions [57, 48]. The Loon Project was looking for building a new layer of the connectivity ecosystem in the stratosphere based on weather balloons with distributed-self optimization [45]. The Loon LLC group tackled the challenge of extending internet access worldwide based on this approach until the project was closed down in 2021 [62, 11]. Another intended sample was Facebook Aquila, yet it has collapsed in 2018 [105].

Another kind of alternatives to cover rural populations include the use of LEO satellites. Besides, LEO and SCPs significantly enable the coverage increase and do not require new terrestrial towers. Therefore, this will offer a highly reliable data rate service, demanding simple but special maintenance attention about its tracing [73]. Figure 2.1 states a feasible implementation of the reviewed solutions in the countryside, aiming to develop the new tendencies considered in the subsection 2.1.3.

2.1.2 Indoor Case

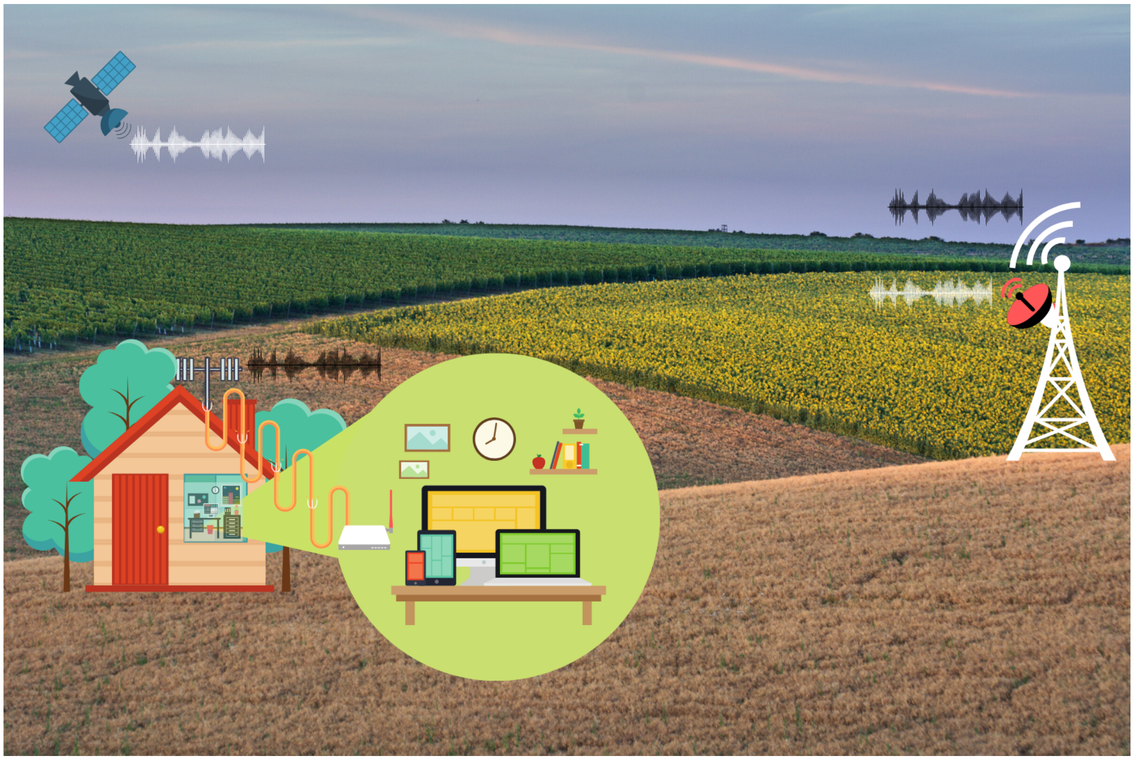


Figure 2.2: Indoor Solution for a Satellite-Based Network

Indoor-improving techniques outline the strategies that enhance the user experience inside closed spaces. Therefore, there is more interference by the physical obstacles. This case requires evaluating the best estimation of indoor coverage provided, looking for optimal system planning. The feasibility to implement algorithmic solutions based on the UE location estimation appears to be challenging since their location accuracy depends on the integrated sensors in the devices by authors said in [99].

The satellite-based networks and other high-altitude platforms suffer excess losses because the slant path intersects several obstructions than terrestrials. Nevertheless, using repeaters at lower frequency bands—despite the bandwidth limitation—can fulfil the requirements demanded from the users [86]. These devices are low-cost and readily available, hence boosting signal propagation meanwhile enhancing indoor coverage may be achieved. Figure 2.2 shows a potential indoor-improvement deployment for a satellite-based backhaul.

2.1.3 New Services

A few years ago, trending services such as IoT and 5G were considered challenging to implement in the rural zones, especially for Latin America, because there were no considerations to grant a reliable and high-traffic supported backhaul network. Nevertheless, these paradigms would hook up dispersed nodes located in remote zones nowadays, with staggering downlink/uplink rates, aiming to accomplish the requirements for Machine-type Communications (MTC) and Narrowband-Internet of Things (NB-IoT) [8].

IoT promises to be a suitable technology to upgrade the countryside—a stable network may be guaranteed meanwhile—following the massive number of connected things and the heterogeneous nature of IoT devices. On the other hand, there is the incursion of MTC application domains, such as agriculture management, transportation, logistics improvement, and crop automation, being one of the fastest-growing telecommunications technologies, especially in urban contexts [75]. LTE-based MTC addresses advantages in increasing the capacity, the traffic response, and the spectral efficiency [107].

Diverse strategies have arisen from assessing the most appropriate technologies to furnish high-speed broadband and reach the desired standard like the service speed, where it is set up at 30 Mbps in European rural areas. Ioannou et al. in [53] state that

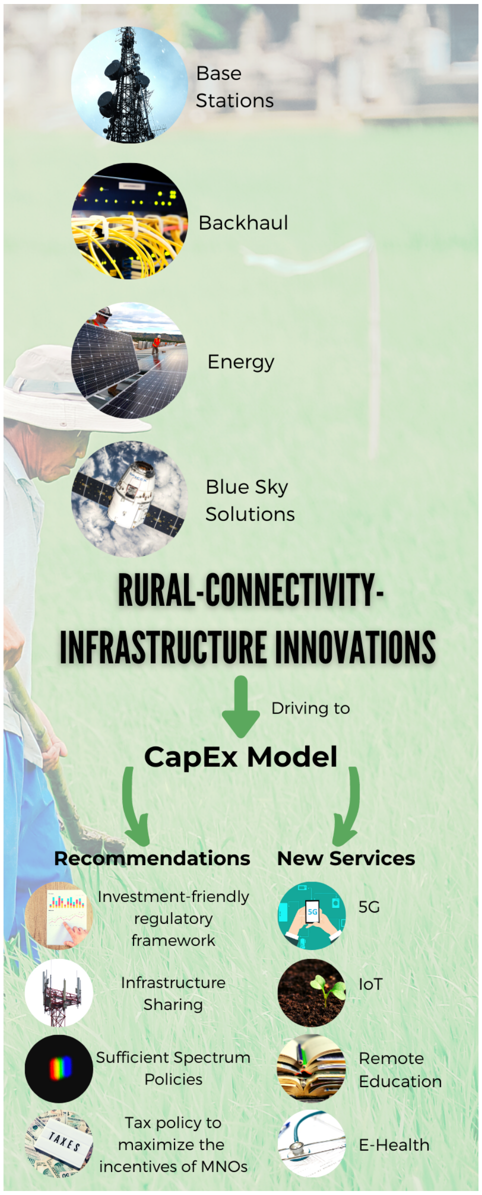


Figure 2.3: Innovations for Rural Connectivity Infrastructure

FTTdp (Distributed Point) solution using G.fast standard performs a cost-effective alternative to VDSL, which the last is the most widespread technology in Europe to grant connectivity in the countryside for now. The authors acknowledge that FTTdP G.fast readily enables bandwidth upgrade, but the model is non-cost-efficient to invest in geographically sparse populations [16, 85].

Consequently, LTE Fixed Wireless Access Networks (LTE FWA) could be an available, attainable solution, bearing in mind the existence of extensive LTE infrastructure in a significant rural part of the world. Whether new-emerged 5G standards are desirable to implement, we can upgrade the LTE FWA through the LTE-NR model, which is the tight interaction between LTE and the New Radio system. The also known model E-UTRA-NR Dual connectivity—or EN-DC—allows benefits in aspects of user throughput in both low and high traffic load conditions [108].

Foreseeing the inclusion of the services mentioned above, the design of Internet access solution should be engaged with the three main factors as the authors outlined in [101]:

- *Affordability*, for avoiding undue hardships by means of reliable networks.
- *Social shareability*, to gain access through selfless (shared) connections.
- *Geographical network coverage*, where networks allow the user's mobility by themselves.

Complementary, the requirements on ubiquitous coverage will not follow the one-size-fits-all standard to pursue a more connected rural society [98].

Figure 2.3 summarizes the information granted by the GSMA's reports [41]-[35], which attempt to state the main driven innovations through an improved roll-out in three foremost aspects:

- *BS infrastructure*, far-flung from the traditional macrocells model.
- *Backhaul planning*, avoiding the higher cost than urban deployments.
- *Energy*, mixing up with renewable sources.
- *Blue Sky solutions*, although those remain in the proof-of-concept stage.

These innovations will move beyond the traditional business model, such as *CapEx*, where the local governments should create new regulation principles to harvest investment in network infrastructure.

2.2 Potential Solutions

There are several challenges to face in rural areas in terms of reliable and enhanced mobile networks. This need triggers the state-of-art study of the diverse network models for the countryside to introduce ubiquitous solutions. All the time and wherever the connectivity shall be available to attend to the population's demands in a fully connected society's eagerness.

By the first attempt to overcome the likely hardships, such as the lack of population enough to deploy infrastructure, adaptive solutions struggle with the current Mobile Network

Operators (MNO) unfolding. The new platforms or devices——that enhance coverage and other rural Key Performance Indicators (KPIs)——leverage practical alternatives for outdoor environments.

There have been studies that cater to the rural coverage through TVWS-spectrum sharing approach where uses free UHF band channels from analogue switch-off in a specific time and space location by the authors says in [13]. Indeed, the primary user (PU) exclusively uses the frequency resources on the bands 470 MHz and 710 MHz.

On the other hand, S. Hasan et al. [42] aimed to recover the GSM whitespace—or the non-actively-used and licensed GSM spectrum—to support the dynamic spectrum sharing; hence achieving a suitable QoS would not be attached to the low throughput and high latency. Regardless, other kinds of solutions have arisen so far to aim for the fully-connected countryside.

In the following subsections, several trustworthy approaches will set forth for diverse rural outdoor solutions, such as Unmanned Aerial Vehicles (2.2.1), Low Altitude Platforms and High Altitude Platforms, and Satellites (2.2.2). Figure 2.1 graphically summarizes the aforementioned solutions to cope with the rural not-spots.

2.2.1 UAV-Assisted Networks

Nowadays, uncrewed aircraft have commercial uses and have enabled new interest in research and innovation toward improving connectivity. The smaller is the airship, the better is the performance to bestow coverage, especially for isolated areas. In this case, the drone industry has addressed several civil instances and applications beneath an affordable and straightforward aim: leveraging UAVs' manoeuvrability to readily provide connectivity as an off-the-shelf alternative within the current MNOs infrastructure.

Historically, the first purpose for Unmanned Aerial System (UAS) was for military and surveillance fields. During the second half of the XX century, the *Warfighter's Internet* [79] yielded a reliable and readily deployment of UAV-based Ad Hoc Network to boost the backbone communications. This exploited-UAS approach led to higher throughput standards. Therefore a network-centric UAS operation concept arose beyond the military and political boundaries, consequently adopted for civil and economic interests. In a nutshell, the uncrewed airships outpaced beyond the soldiery endurance.

Table 2.1: Specification for UAV According with the Context

Scenario	**Network Parameters**					**Context**		
	LHT [m]	UHT [m]	BMP	LOS	NLOS	Use Case	Network Configuration	Flight Time [min]
UMa-AV	22.5	100		X		HD M2H	5G	TBD
UMi-AV	TBD	TBD			X	M2H	LTE/LTE+	15-45
RMa-AV	10	40	X	X		L2M LD		60-180

Since an expedited drone spread-over-the-air has lifted recently, the need for regulating them has arisen as well, complying with the safety standards, even though they reached lower altitudes than other larger kinds of aircraft. Therefore, Global Unmanned aircraft system Traffic Management Association (GUTMA) appears to foster the trustworthy, secure, and efficient integration of UAS into global airspace [3], addressing drone stakeholders practices—defined as UTM stakeholder—by close cooperation and continuous flights information management.

To lend a collaborative and innovative community for UTM stakeholders, GUTMA encourages the governments to adopt operation-centric, heading for safe, fair, and secure deployment of UTM solutions. Besides, for allowing full integration of UTM services with current network infrastructure, the first step should foresee the digitalization needs of UAS technology trends [4]. Once set it forth, Table 2.1 compiles some of the key specifications for the UAV-assisted network in line with the deployment scenario, namely urban, suburban, and rural contexts.

Table 2.2: Some Surveys of UAV-based Communications

Publication	**Brief Summary**	**Approaches Fields**
Mozaffari et al. [72]	A fair of potential benefits and applications of UAV-based communications in the enhancing coverage, capacity, and reliability of wireless networks eagerness.	The key UAV challenges hold 3D deployment, performance analysis, channel modelling, and energy efficiency. A comprehensive overview on potential applications, chief research directions, challenging open problems, among others.
Li et al. [61]	A noteworthy integration of 5G technologies with UAV communications networks upon an emerging space-air-ground integrated network architecture.	Space-air-ground integrated network envisions for Beyond-5G Communications. 5G techniques for physical and network layer of UAV scheme, and joint communication, computing and caching.
Fotouhi et al. [32]	A development summary promotes the smooth integration between UAVs and cellular networks without a one-size-fits-all but affordable model.	The authors surveyed the interference issues, and potential solutions on UVA-base flying relays and BS approaches. The article sets forth the new regulations and protocols to grand the cyber-physical security in both aerial nodes and UEs.
Shakhatreh et al. [93]	An exhibition of next big revolution in civil applications by introducing UAV technologies to state feasible research trends and future insights.	Addressed civil applications: Road traffic's real-time monitoring, wireless coverage, remote sensing, search and rescue, surveillance, civil infrastructure, among others. Discussed key challenges: Charging, collision avoidance, security, and networking.
Khawaja et al. [58]	Modelling of Air-to-Ground (A2G) propagation channels in designing and evaluating stages of UAV communication links attempts to improve the AG channel measurement campaigns.	AG wireless propagation channel research includes payload communications and control and non-payload (CNPC) networks. The AG channel study tackles limitations as large and small scale fading.
Hayat et al. [43]	The aerial network missions should vary according to the civil application aims.	Search and Rescue Coverage Network Coverage Delivery/Transportation Construction

The gathered information—in the Table 2.1 —divides up the network features into two correlated fields: the target scenarios and the use case context. Concerning the first, Muruganathan et al. approach to the stakeholder populations and their LTE network's technical deployment in such as Urban-macro with aerial vehicles (UMa-AV), Urban-micro with aerial vehicles (UMi-AV), and Rural-macro with aerial vehicles (RMa-AV) [74]. The second considers zones density, emphasizing the Highest (HD), the Medium-to-High (M2H), the Low-to-Medium (L2M), and the Lowest (LD) [5].

An analysis of coverage issues should extend the operational scope through defined network architecture to successfully deploy aerial communications. A first option unleashes a unique-UAV model by hooking up one or several Ground-BS (GBS) and the drone acting as a relay node into the network. Secondly, a swarm of drones seems suitable to cover a vast extension or rural dispersed nodes, creating a solid construction of Flying Ad-Hoc Networks (FANET) networking. The last strategy outpaces the challenging issues that Mobile Ad-Hoc Networks (MANET) were tackled in terms of communication range since a ground node can indirectly communicate with other hops through several aerial relay nodes such as UAVs [89].

The concept of FANETs has arisen in the literature to top off with a particular form of Vehicular Ad-Hoc Networks (VANET) communications and addressing for scalable, reliable, real-time peer-to-peer mobile ad-hoc networking between aerial and ground nodes [88]. Table 2.2 relates some UAV-based communication surveys, where the authors have thoroughly reviewed the UAS modelling strategy in fields such as civil, security, traffic management, among others.

The approaches as mentioned earlier, among others, are comprehensively explained in Table 2.3 and Table 2.4. The first acknowledges the literature of UAV-based networks between twenty years ago and five years ago, which states the strategies that the cited authors assessed for expanding MANET coverage primarily by algorithmic solutions. The second leads our survey to the outstanding aim: to figure out the promising models for rural communications, raising the current cellular infrastructure, or even adopting a new topology for ubiquitous coverage.

Table 2.3: Phases of UAV-Based Network Models

PHASE	APPROACHES	STRATEGIES / MODELS	ADVANTAGES / FINDINGS
Early: < 2011	Military Services	Airborne Communication Nodes to form a backbone network for Warfighter's Internet [79].	Allowing connection for separated forces Reliable and easily deployed
		The biologically inspired-metaphor algorithm of bird flocking for UAV nodes' placement and motion, adapting their mobility [21].	Especially useful for rugged and mountainous terrains with heavy signal attenuation. Achieving a stable connection and load balancing.
		Dynamically placing UAVs considered as relays nodes to provide full connectivity in a disconnected ground MANET through heuristic and algorithmic approach [26].	Location tracking that allows an optimal interaction between ground nodes and UAVs without introducing new MANET protocols. Cost reduction based on finding the minimum number of needed UAVs.
	Integrated Architecture	Two-level Satellite empowered architecture (HAPs/UAVs + Satellite) to improve the limited coverage, guaranteeing superior bandwidth access [81],[82].	Allowing interconnection with remote locations. Enhancing hot-spot coverage with low latency rates. Mitigation of shadowing impairments through a HAPs/UAVs repeaters-configuration.
		Implementation of UAV-HALE (UAV-High Altitude Long Endurance) platform as a base station with an adaptive antenna array [31].	Covering rural low-densely populated areas and isolated-by-relief regions. Support the telecommunication system in emergencies. Assist hot-spots traffic with a lower cost solution Provide higher QoS, increasing capacity, and keeping lower computational complexity.
		An algorithmic solution to state and hedonic coalition formation, consisting of a determined number of UAVs continuously collecting packets from task arrays [87].	Performance improvement, based on the self-organization of air nodes and tasks into independent coalitions. UAVs can assess the decision to act as collectors or relays(to enhance wireless transmission). Suitable model to tackle several aims as surveillance or wireless monitoring.
		Evaluation of A2G links coverage using UAVs at altitudes up to 500 m, performing as a radio relay platforms in low RF environments [37],[25].	Support over 90% coverage of the ground receivers within 10 dB of LOS Path Loss. Excellent connectivity for low flying UAV in limited urban areas considering SWAP, even for buildings-blocked receivers. For higher altitudes, the coverage becomes homogeneous in rural zones.
	MANETs Upgrade	UAV-assisted MANET model, which is rooted in 4 connectivity regards: global message (successful propagation to all nodes), worst-case (dividing up a close network), bisection (division cost), and k-connectivity (failed nodes threshold before a disconnection) [40],[39].	The aerial nodes can generate, receive, and forward data packets; or improve network connectivity and availability. The model will achieve better QoS and coverage. As the proposed method, an adaptive heuristic algorithm can provide a simple solution and reach a better performance.
		Performance assessment of Ad Hoc routing protocols, like GPRS, OLSR, and AODV, in the context of swarms of UAVs, also considering the relative location of destination nodes [47].	Maximize the throughput with a minimum number of neighbors into the swarms to ensure connectivity. Minimize power consumption and optimize the loiter time to prevent cross-interference and redundant transmissions through spatial multiplexing technique.
		Ad-Hoc UAS-Ground Network (AUGNet) solution, where an Unmanned Aircraft provides additional connectivity for ground nodes, driving into shorter routes with better throughput [23].	Improve the connectivity at the network coverage boundary. Introduce the net-centric UAS operation concept, a tight coupling between communications, mobility, and task fulfillment.
Medium: 2011 – 2016		Mobility strategy for UAV-compound MANET to support communication data flow between ground nodes in a dynamic topology network [46].	Provide the most appropriate air nodes position that maximizes network performance. UAV nodes can flexibly communicate with ground nodes in the LOS, covering a greatly extended area. Ground nodes periodically grant their communication status to the air-backbone to find the best mobile strategy.
		Analysis of the coverage problem to aboard several issues in UAV-FANETs, expecting to extend their operational scope and range, and a reliable response time [89], [88], [28].	The solid construction of FANET networking standards will lead to scalable, reliable real-time peer-to-peer, new-form MANETs. Aim to the robustness of the coverage algorithms, considering the several constraints in these kinds of networks, especially for UAVs fleets. Cooperating UAV form aims to increase reliability for aerial missions, ensuring the connectivity of non-LOS systems.
	Connectivity/ Coverage Enhancement	Approach established on a neural-based cost function to improve coverage and boost capacity into geographical areas subject to high traffic demands [94].	Provide reliable multi-connectivity using UAS overview as relays between a disconnected network and enhance connectivity. The model can provide better capacity, reliability, and prolonged connectivity to tackle the inefficiency in handling macro cellular networks traffic demands.
		The connectivity-based mobility model (CBMM) compares coverage and connectivity performance, looking for an optimal tracing and sense of a given area [106].	Monitor inaccessible or dangerous areas to deliver information with lack-of-infrastructure regions. CBMM allows adapting air nodes direction to maintain steady links to ground stations or their neighbors. Reduce the overlap between covered areas, using an efficient and limited number of UAVs with a specific spatial density.
		Efficient 3D deployment of multiple UAVs as portable Base Stations, seeking the downlink coverage performance's maximization, whereas using a minimum transmit power and directional antennas [70].	Aerial Base Stations have a higher chance of LOS links to ground users. UAVs can readily move and have a flexible deployment to provide rapid, on-demand communications. Using directional antennas, the model may enhance UAV-based networks because of effective beamforming schemes.
	Deployment Focusing	Low Altitude Small UAVs (SUAV) pilot provides a micro-scale mobile communication relay, attempting to a superior propagation model and increasing bandwidth reuse for emerging traffic hotspots [38].	The model achieves an improvement of mean throughput (>22%) and QoS (>70%) in both rural and urban environments. Offer new possibilities for addressing local traffic imbalances and providing great local coverage.
		Deployment of Drone Small Cells (DSCs), or aerial wireless base station, to optimize the covered area. In the presence of D2D users, new challenges -as coverage performance- should be tackled [71],[69].	The optimal UAVs' altitude leads to the maximum coverage and system sum-rate simultaneously when introduces into underlaid D2D communications links. In the case of 2 or more DSCs, an optimal separation distance will grant maximum coverage for a given target area.
	Civil Applications	QoS requirements ranking of UAV networks marked into a practical choice for commercial applications. These aims will outline the design of emerging aerial networks [43].	Delimitation of the missions into four categories: Search and Rescue, Coverage Expanding, Delivery/Transport, Construction. SUAVs have turned into handy but inexpensive options for commercial aims due to their their ease of deployment, low maintenance costs, high-maneuverability and ability to hover. Wi-Fi technology can support several of the prior categories whether each application requires a few number of hops amongst the nodes.
		UAV-aided Wireless Communication may be a promising solution for scenarios without coverage infrastructure [109].	UAV systems are more cost-effective than other solutions –such as HAPS and satellites–, providing performance enhancement and adaptive communications. UAV-based networks involve three typical use cases: *ubiquitous coverage*, *relaying*, and *information dissemination and data collection*.

Table 2.4: Phases of UAV-Based Network Models (Continuation)

PHASE	APPROACHES	STRATEGIES / MODELS	ADVANTAGES / FINDINGS
Novel: **> 2016**	Rural Panorama Addressing	Energy consumption optimization aims to improve the aerial node missions and connectivity in the countryside through a graph-based structure model called RURALPLAN [54],[29],[14].	The multi-period graph approach derives into Genetic Algorithms. It guarantees the coverage and the efficient management of the UAV consumed energy. RURALPLAN can reduce energy consumption by up to 60%. The deployment of UAV-based networks can adopt a short-distance LOS, decreasing the installation costs. By considering a set of optical fiber links to support the backhaul network, the capital and operation expenditures can be compensated, simplifying the stated model.
		Analysis of joined-architecture networks, mixing UAVs and GEO/LEO satellites, to increase the radius coverage and state the usability of aerial nodes to assist fixed-infrastructure networks in the countryside [24],[36].	The use of aerial nodes, acting as relays, can cover vast rural extensions, addressing further mobile network generations—such as 5G—to implement steady-links IoT devices. Bearing in mind the optimizing cellular networks aim in the countryside, heritage functionalities of LTE can achieve prominent coverage radius in the sub-1 GHz bands, raising the RF propagation. Since Non-Terrestrial Networks may be an integral part of the 5G infrastructure, UAVs become on the bedrock of a mixed-architecture network, especially in collect data in the massive MTC types of application.
		LTE networks can provide coverage by UAV nodes in rural areas, chiefly to boost the Command and Control downlink channel, despite the raised interference due to height dependency [60], [78].	The dependency of the large-scale path loss on the drone's height may be challenging to achieve significant growth in coverage level, boosting the aerial-node perceived interference level. Applying the network diversity, it is possible to improve the network coverage level and its reliability, since SINR would be better than the achieved -6 dB index, under the full-load assumption. The interference conditions—because the drastically-change UAV height— will determine the channel characterization to assess the wireless remote control for the aerial nodes.
		Boosting aerial coverage of rural area network deployment to clear limitations by interference mitigation techniques [77].	Interference canceling and antenna beam selection are strategies to improve the overall—aerial and terrestrial— system performance. The abovementioned schemes will gain a 30% of throughput and achieve a 99% reliability increase. Downlink and uplink radio interference trigger poor performance within aerial traffic.
		A Non-Orthogonal Multiple Access (NOMA) layout for UAV-assisted networks, to provide emergency services in rural areas [44].	The proposal carry out the performance of terrestrial users enhancement,leading a the by-device consumed energy minimizing. The proposed user-centric strategy follows stochastic geometry approaches for terrestrial users –placed into Voronoi cells– served by UAVs, achieving the location model of both nodes and UEs. In the case of the NOMA-assisted multi-UAV framework, the analysis of coverage probability can aim to set properly up the network's power allocation factors and targeted rates.
	Cellular Network Advance	Optimization of the UAV-mounted base stations (MBSs) placement, setting forth a Geometric Disk Cover (GDC) algorithmic solution, which coats with all ground terminals (GTs) in an inward spiral manner [63].	The correct deployment of MBSs can cover a set of k nodes with a minimum number of disks of a given circular surface with radius r. The computational complexity may be significantly reduced when the coverage starts from the perimeter of the area boundary.
		The Path Loss (PL) Characterization for urban,suburban, and rural environments enhances the access technologies for low-altitude aerial networks, considering the UAV height effects on the channel [9],[104].	By introducing a Correction Factor (CF), which relies on the UAV altitude, the large-scale fading and the PL of the A2G channel will be accurately characterized. In urban contexts, PL increases with the horizontal distance. In the case of rural zones, PL is irrelevant to the UAV heights. Albeit it approximates to free-space propagation model at heights around 100 meters. UAV-based networks face a large amount of neighboring interference due to the down-tilted antenna pattern of cellular networks. Besides, the coverage behavior will be affected beneath this scheme.
		Improvement of coverage and capacity for future 5G configuration of aerial networks beneath two algorithmic approaches, entropy-based network formation [95], and latency-minimal 3D cell association scheme [68].	By correctly select the UAV controller and then performing network bargaining, the aerial base station could top off a more remarkable improvement on its throughput, SINR per UE capacity in the order of 6.3%, and minimal delays and error rates. With the increase of simultaneous requests within the next-generation heterogeneous wireless network, entropy approaches appear to be suitable to overcome the UAV allocation and Macro Base Station decision problems. Lifting 3D configuration for aerial cellular networks, a yield in reducing up to 46% in the average total latency would enhance spectral efficiency.
		Optimal design of aerial nodes trajectory in cellular-enabled UAV communication with Ground-BS (GBS) subject to quality-of-connectivity constraints about the link GBS-UAV [110].	The optimization problem converges in a non-convex approach to find high-quality approximate trajectory solutions. Channel's delay-sensitive rates and SNR requirements restrict the target communication performance. UAV's mission completion time may guarantee an efficient method for checking the strategy's feasibility.
		Cooperation of small and mini drones can further enhance the performance of the coverage area of FANETs —even other aerial-kind networks—by establishing a hierarchical structure of efficient collaboration of drones [103], [102].	In the case of ultra-dense networks, the approach efficiently broad the common issues such as sparse and low-quality coverage and the non-steady aerial links. The rapidly unfolding of UAV carries out in non-dependency of geographical constraints and implies a system performance lifting by establishing almost LOS communication links in most scenarios. Among other advantages—at the top of cooperative distributed UAV networks— are the distributed gateway-selection algorithms use and the stability-control regimes.

Regulation

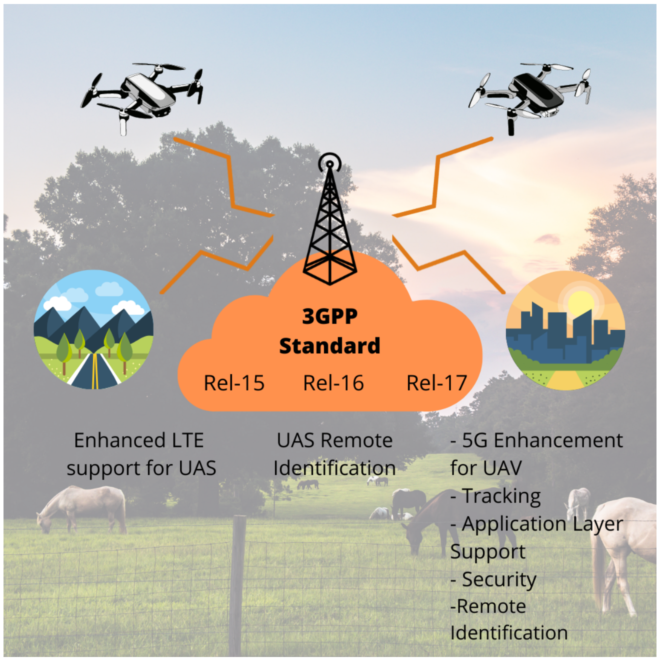


Figure 2.4: UAS Addressing in 3GPP Standards

The 3GPP Association mainly tackles the protocols and regulations for UAS-FANET communication, beneath the addressed need of the quickly maturing sector [7]. Consequently, in the eagerness to state new studies and new features for a safe operation, there has been joint work with GUTMA, even involving the novel 5G framework use cases. To best awareness, Figure 2.4 introduces the areas that are being addressed in the latest 3GPP Releases, from Release 15 to Release 17.

There are further institutions concerned with UAS in-development standards, such as GUTMA/GSMA, ASTM International, IEEE, ISO, EUROCAE, IETF, and JARUS [4]. For a ready insight of the network safety, by avoiding a loss of service due to their proximity, we have briefly recapped the 3GPP suggested edges [7] as long as new releases will emerge on enhanced LTE support [74]:

- *Release 15* addressed the research studies about the ability for UAVs to be served using LTE networks, besides a comprehensive analysis of potential interferences between eNodeB and UAS.

- *Release 16* has an overview of the potential requirements and use cases to enable the necessary connectivity between UAS and UTM.

- *Release 17* approaches the use cases and requirements for UAS identification and tracking beneath the application layer. It also gathers the 5G connectivity needs of drones in new KPIs into a 3GPP subscription.

2.2.2 Other Engaging Solutions

We have thoroughly reviewed the implication to assist rural networks by employing UAVs; besides, there have been other engaging solutions that can enable broad coverage in the countryside to shed light on its connectivity. On the 2000s' onset, SCPs appeared to be a prominent answer for fixed and mobile applications. These devices remarkably outpaced the unprofitable gap since they have arisen as a cost-effective solution for urban, suburban, and rural areas [49].

Aside from dedicated area coverage independence, authors in [49] pointed out that Sky Station platforms may provide higher capacity—by higher frequency reuse—-than other wireless systems, the possibility of grant enhanced roaming, as well as choosing their stationary point. Another seamless option for rural connectivity has been the satellites, namely LEO configuration. The following sub-subsections are going in-depth of the aforementioned strategies, whereas the UAVs also fall into this category.

Altitude Platforms

The altitude platforms are grouped into LAPS (Low-altitude platforms) and HAPS (High-altitude platforms). Song et al. in [97], granted the main difference about the prior categories. LAPS gather the aerial platforms at an altitude down of 20 km. UAV, drones, and blimps fall into this group since they cannot support higher payload capacities, and their autonomy relies on SWAP constraints [22]. As subsection 2.2.1 in-depth met, UAVs can perform far-flung coverage, increase the redundancy, and increase survivability, leveraging the swarm FANET architecture [97].

LAPS have lent dynamic and scalable network which can cover quickly broader regions, although there are by-payload stuck. In this case, there are two ways to limitation tackling: First, developing a suitable propagation model that includes the elevation angle—deployed at several altitudes— along with the MIMO output antenna diversity gain, especially for the last mile connectivity [12]. In the UAV case, the strategy may contain a formulation of statistical assessment of A2G propagation by either using Ray Launching or Ray Tracing geometrical optics models [19]. Second, Drone-to-Drone communication arises as reliable collision avoidance system [22].

On the other hand, HAPS operate in a quasi-stationary position at an altitude of 20 to 50 km, becoming a viable option to furnish capacity and coverage enhancement [97]. Authors in [10] have envisioned these platforms as a super macro BS (HAPS-SMBS), to unfold high-traffic-volume networks in a metropolitan area to bargaining with the smart city paradigms. Facing the LEO constellation shortcomings, HAPS-SMBS can mask the high path loss and the high mobility effects.

The potential uses of HAPS—to tackle the rural not-spots—shed light on dynamically manage radio resources and mitigate the crossed interference [20]. The rural environment has admitted more prevalence to network coverage instead of higher capacity density. The reason why HAPS needs a lower investment and providing high quality—even providing higher terrestrial QoS— has carried out this alternative to cover rural and remote areas [92]. At this point, likely exploitation of radio environment maps and artificial intelligence on the ongoing infrastructure may allow a radius coverage area of more than 30 km, as Chukwuebuka highlighted in [92].

Satellites

Satellite-based architecture has furnished an outstanding architecture to hook up the highly dispersed and remote rural nodes due to their scalability and flexibility to reach vast geographical areas. In function of the developed network scope, the satellites' orbit unleashes a defined classification [100]: LEO (altitude between 500 km and 2000 km), MEO (altitude into the range 5000 and 20000 km), GEO (altitude of 35800 km).

Underneath the condition of service-as-primary-resource, LEO architecture, on the one hand, solve the latency issues; on the other hand, it has added remarkable bit rate capacity by multi-beam technology [15]. In contrast, e.g., GEO holds limited these parameters. Heading to the best alternative for rural not-spots, LEO has become the best complementary structure of terrestrial networks in the countryside, figuring out several shouldered challenges, such as routing problems and raining attenuation [18].

To provide seamless and continuous service by LEO satellite networks, these have adopted constellation shape whereas QoS is guaranteed, fueled by novel routing protocols regarding UE location and exploiting the deterministic LEO topology. Therefore, the route bottlenecks should be foreseen in any pair of end-users, as the authors said in [111]. By avoiding the design planning deficiencies, the greater system's user capacity, the wider the covered geographical zone [18].

Chapter 3

Methods & Materials

3.1 Materials

In section 1.4, the methodology was presented to readily dive into the procedure that assesses the proposed aim of the current research. After identifying the stated solutions for bestowing the rural coverage in the chapter 2, the final target—to prove the plausibility of the stated hypothesis—surrounded the reproduction of a UAV-based receiver—since the UAS appears to be the most affordable option to undertake the rural connectivity—which are consisted of the components arranged as follows.

3.1.1 SIM900 Shield

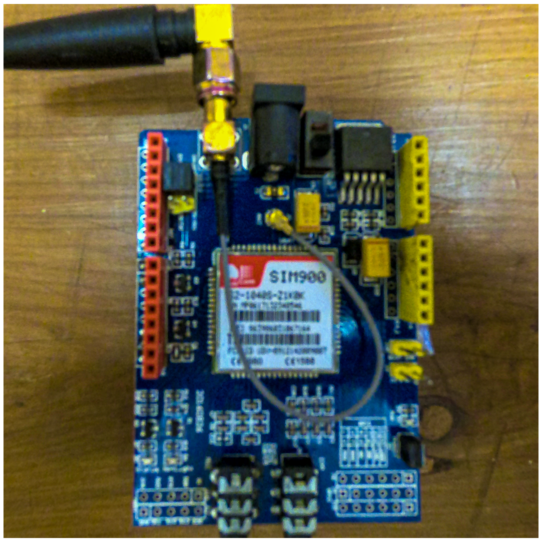


Figure 3.1: SIM900 Shield

The SIM900 GSM/GPRS—displayed in Figure 3.1—is a 2.75G modem that allows SMS, phone calls and connectivity through Enhanced GPRS (EGPRS). Its construction includes a shield and microprocessor which can plug with other devices such as Arduino. Among its main features, it is possible to leverage the listed below [6].

- Holds up Quad-band: GSM850, EGSM900, DCS1800, PCS1900.
- Supports GPRS data with TCP/IP and HTTP.
- Owns a transmit power of 2W (Class 4) for GSM850 and 1W (Class 1) for DCS1800.

Other noteworthy aspects include establishing a connection with Arduino using UART protocol with baund rate $\Delta b \in [1200 - 115200]$ bps. Beneath a master-slave configuration, the shield may be addressed employing AT command set. Its operating voltage falls into the range $[3.4, 4.4]$V, and finally, it owns 2A as a maximum current draw during the transmission burst.

3.1.2 Arduino UNO

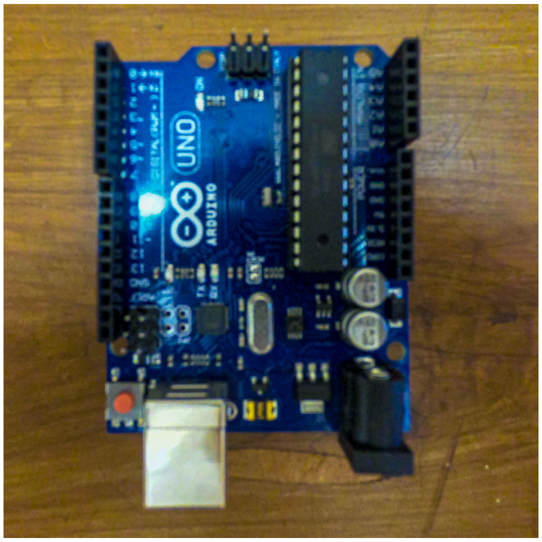


Figure 3.2: Arduino UNO Platform

Arduino—displayed in Figure 3.2—is an electronic board based on easy-to-use hardware and software [17]. The device has been trending in the last years because it is easy to program by using the Processing-based integrated development environment (Arduino IDE), that allows active development of specific but high-level projects in academic prototypes.

The versability of Arduino allows handling the SIM900 shield through the *AT Commands*, which is a set of strings that can operate a modem by serial communication between the master and the slave model. Since the *GSM 05.08* [51] specifies the AT style commands for controlling the GSM modem, the leveraged queries to cope with the network parameters are presented below.

- `AT+CREG?`: Checks if the shield is registered to either the local network or roaming.
- `AT+CSQ`: Provides the RSSI—in dB—and the channel's BER of the subscribed network. The inquiry provides the correlated code to the mentioned parameters which should be mapped in the stated decoding table, given in the GSM Technical Specification GSM 05.08 [51].

3.1.3 TELLO Drone

Tello Drone is a tiny quadcopter with a visual location system and on-board camera. Its extending flight time is roughly 13 minutes in windless conditions, and the maximum reachable distance is 100 m. The device can support a maximum payload—under extreme conditions—of 80 g. With the SDK interface, the device can connect with remote control through a Wi-Fi UDP port fueled by a Python algorithm to establish a full-duplex communication.

To stifle Tello's shortcomings to lift transcendent payloads, Figure 3.3 states the gathered appliance composed by Arduino+SIM900 shield. With this construction, the UAV could elevate the assessing device

Figure 3.3: Tello Drone and The Compacted Device

and then collected the test data for the experimental stage. In section 3.2, the process will be in-depth explained to envision the challenges in the current step.

3.1.4 Other Used Equipment

Striving for an enhanced gadget conformed to the devices, as mentioned earlier, adding a portable battery would improve the structure of the desired prototype. In this case, the portable battery Tplink TL-PB10000 was leveraged to guarantee the power requirements of both the Arduino and GPRS modem since it has a capacity of 10000mAh with 2 USB type A interface ports, which bestow 5V/2.1A at the output.

3.2 Methodology

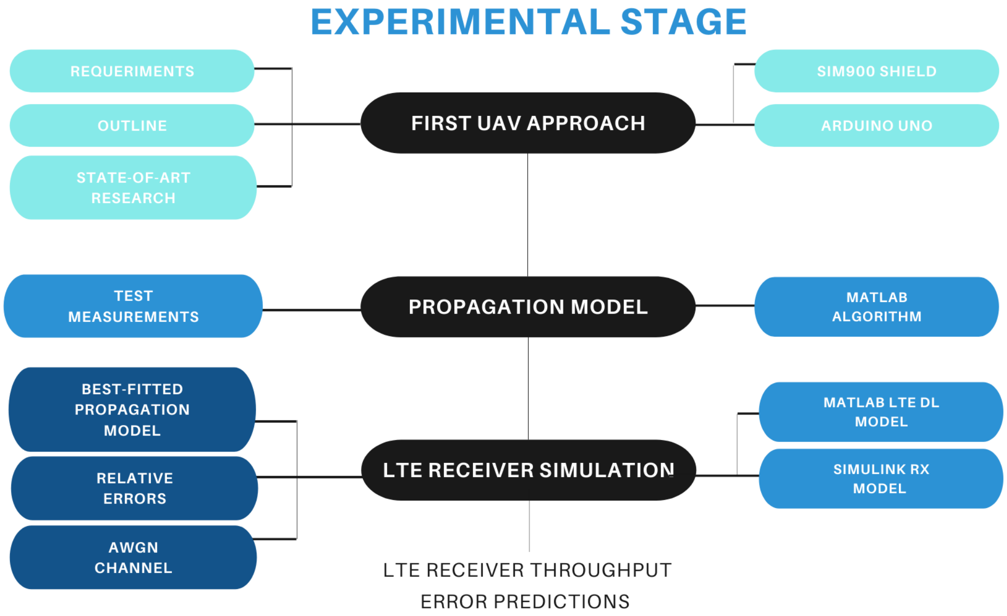


Figure 3.4: Phases of the Experimental Stage

Figure 3.4 exhibit the main phases of the experimental stage that used the above-stated equipment to yield the respective hypothesis testing. The following sections go deeper into each process and explain their particular scope to support the plausibility of the experiment.

3.2.1 First UAV Approach

The used UAV's hardships should be evident, yet the implemented strategies to overcome the supported payload deficiencies of Tello, which would envision the possibilities to upgrade the experiment further. Consequently, by adopting a cloud server, such as *ThinkSpeak*, it was

UAV First Approach

Channel ID: 1316280
Author: diegocabrera06
Access: Private

The channel contains the SIM900's retrieved information for the Experimental Stage to produce test measures.

Channel Stats

Created: 2 months ago
Last entry: 20 days ago
Entries: 27

RSSI [dBm]: -87
Sun May 09 2021
18:53:36 GMT-0500

BER [%]: 0.14
Sun May 09 2021
18:27:59 GMT-0500

Figure 3.5: ThinkSpeak Server Outline

possible to drop out the extra shield that aims to save the reaped information of the core device without adding extra weight over the UAV.

ThinkSpeak is an IoT server that allows developing live data applications by information upload in the Cloud. It owns a straightforward integration with MATLAB since the platforms are part of the Mathworks family. Based on channel processing, it can sense several real-time parameters simultaneously as long as three main processes cater to the analysis: Collect, Analyze and Act [67].

Figure 3.5 introduces the ThinkSpeak outline with real collected data. It contained two information channels. On the one hand, the RSSI level regarding the harvested time; on the other hand, the received signal quality was analyzed through the mapped BER and displayed on the right-side channel. To fully take advantage of the server's features, it was crucial to fuel the cloud by using the SIM900 TCP/IP port as long as the Arduino commanded the respective AT queries on the GPRS shield.

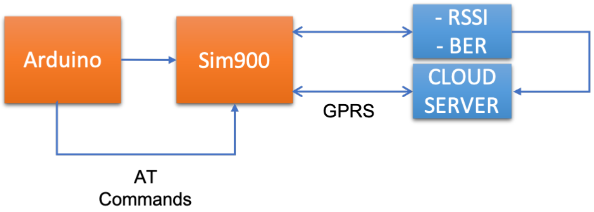


Figure 3.6: Flow Chart of Data Gathering Step

Previously to the data charging procedure of the Thinkspeak server, it is necessary to collect the mobile network RSSI and BER. To this end, Figure 3.6 displays the flow chart of the data gathering process. As a result, for shedding light on the analysis of the proposed hypothesis, the tied version of the Arduino+GPRS shield allowed measuring the actual status of the mobile network in the elected rural community. Regarding the prototype's interface, the ETSI's GMS 05.08 sub-clause 8.2.4 in [51] specifies the radio sub-system link control that should be bestowed in the Mobile Station (MS), BS, and Mobile Switching Center (MSC).

The served displayed both signal strength (RXLEV) and signal quality (RXQUAL) indicators. Due to the performed AT command `AT+CSQ` provided the coded parameters, it was imperative to map the network's RSSI by using the following linear relationship.

$$\mathrm{RSSI} = 2 \cdot \mathrm{C} - 113 \tag{3.1}$$

In equation (3.1), the code C—brought by the AT command—has a dBm units, likewise RSSI has. Concerning the channel's BER, the parameter RXQUAL could have mapped by using the Table 3.1 table.

Table 3.1: Signal Quality Mapping

RXQUAL	**BER Range**	**Assumed BER** [%]
0	$[0, 0.2)$	0.14
1	$[0.2, 0.4)$	0.28
2	$[0.4, 0.8)$	0.57
3	$[0.8, 1.6)$	1.13
4	$[1.6, 3.2)$	2.26
5	$[3.2, 6.4)$	4.53
6	$[6.4, 12.8)$	9.05
7	≥ 12.8	18.10

To envision the code structure of the implemented algorithm in Arduino—using its IDE—the Appendix A thoroughly meets the involved algorithm from the data acquisition until the cloud server's upload.

3.2.2 Propagation Model

Diving into the AGC design—comprenhensivley studied in chapter 2—Table 3.2 displays the selected reference parameters and the model type for a rural aerial channel, retrieved from [58], to evaluate the feasibility of the performed Measurement Campaign.

Table 3.2: Reference AGC Parameters

Scenario	**Reference**	**Path**	**Model type**	**PLE**	σ
Urban, Rural	[58]	LOS	Log-Distance	4.1	5.24

Beneath the reference parameter consideration, the Measurement Campaign establishes the propagation testing plan, which encompasses essential issues such as BS location, testing routes, testing guidelines, among others [90]. Consequently, several measures were collected randomly with their respective geographic coordinates to meet them up with the respective RSSI, or—in LTE case—with their RSRP (Received Signal Reference Power).

Figure 3.7 provides the information of the assessed mobile network in a near rural settlement called *Gallinazo* in Manizales, Colombia. Each taken point P_i owned an RSSI value

Figure 3.7: Assessed Rural Mobile Network in Colombia

in the range from -63 dBm to -103 dBm. To clarify the network incidence over P_i, it follows a bubble map notation which retrieved a proportional ratio to the network's signal strength. The context details were treated, such as the traffic time, the climatic conditions, and the likely signal obstructions. Therefore, Figure 3.8 introduces some pictures of the evaluated environment, including the UAV receiver rollout.

After performing the foregoing outlined process of measures georeferencing, the RF propagation modelling relies on the distance of the likely receivers from the transmitter location, beneath an accurate construction of the propagated signal coverage map. To this end, each point P_i should be related to its *geographic distance*—by determining the geographic distance through the Haversine formula—from the transmitter site or BS site.

Beneath the aim of leveraging the best propagation model, straightforward path loss patterns were assessed, such as Free-Space, Two-Ray, Floating-Intercept (or L_{50}), and finally, the Close-In model. Table 3.3 states the formal expression of the preceding models, where the distance to the BS site—or reference point d_0—becomes the main parameter of them. Usually, the reference distance is set up in 1 m, which will not be the exception.

Figure 3.8: Pictures of the Rural Community in Colombia

Table 3.3: Used Path Loss Models

Model	**Expression**
Free-Space	$PL(d) = -27.55 + 20\log(d \cdot f)$
Two-Ray	$PL(d) = 40\log(d) - 20\log(h_{Tx} \cdot h_{Rx})$
Floating-Intercept	$PL(d) = \beta + 10\alpha\log(d)$
Close-In	$PL(d) = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right)$

From Table 3.3, there are several variables that it is worthy of setting up. The transmitting frequency: $f = 850$ MHz (Claro Colombia MNO Band 5), the transmitter and receiver heights respectively: $h_{Tx} = 30, h_{Rx} = 1.5$ m, the reference distance $d_0 = 1$ m, the independent variable of distance d, the Path Loss Exponent (PLE): n, and α, β envision the linear regression parameters of the L_{50} model (slope and intercept). The last three parameters were the main target of the current phase.

Finally, the algorithm in Appendix A is heading to obtain the parameters mentioned in the above paragraph leveraging the MATLAB's versability with its Antenna Toolbox [65]. In section 4, there are presented the primary outcomes to assess the stated hypothesis.

3.2.3 LTE Receiver Simulation

In the section 1.4 pointed out that the COVID-19 pandemic limited the Measurement Campaign in terms of collecting data enough to guarantee the construction of accurate and precise models. Nevertheless, it was not a significant bottleneck in the eagerness to evaluate the viability of unfolding UAV-based networks to strive against the connectivity gap in the countryside.

Alternatively, both MATLAB Antenna Toolbox and LTE Toolbox [65, 66] were the outstanding solutions to spur the main aim of the project with the boundless advantage to construct the pursuit model. By leveraging the provided algorithm, namely a formal example of modeling and testing and LTE RF receptor—stated in Apendicce C—without overlooking the accomplishment of the experimental stage, Figure 3.9 shows the flow chart corresponding to the LTE Receiver Simulation phase.

Figure 3.9 states the main parts of the simulation, which a generated LTE waveform—using the LTE Toolbox—were filtered and transmitted through a propagation channel with AWGN seed before feeding it to the RF receiver model, carried out with RF Blockset and based on available off-the-shelf parts. EVM figures were then provided for the output of the RF receiver to analyze the network frames throughput. The main features of each block will be explained in the following sub-subsections.

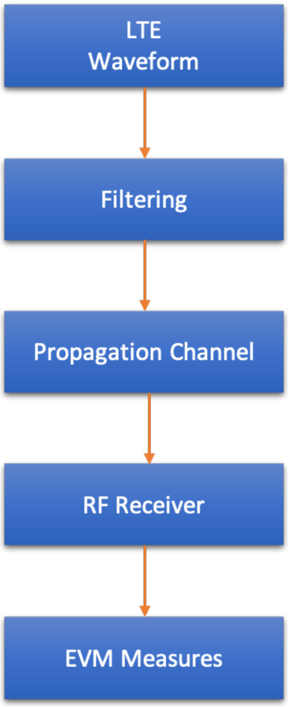


Figure 3.9: Conforming Blocks of LTE Receptor Simulation

LTE Waveform

This block contemplated the generation of LTE Waveform, placed on the Reference Measurement Channel (RMC) R.6—defined in [1]—which has leading parameters such as reported below.

- Bandwidth: 5 MHz.
- Resource Elements (RE): $25/\Delta B$.
- Modulation scheme: $64-$QAM.
- Noise figure: $Noc = -98$ dBm per subcarrier (15 kHz of bandwidth) and produced by the OFDMA Channel Noise Geneator (OCNG OP.1 FDD) in the unused REs.

Filtering & Propagation Channel

By using the results in the Propagation Modelling phase 3.2.2, the simulation lent the following requirements.

- Order 32 Band-limiting Filter.
- Passband frequency: $f \in [2.25, 2.7]$ MHz.
- Propagation Model: Free-Space Path Loss with equation $PL = -10\log_{10}(E_s)$, where E_s: Symbol's Energy. The Energy of the symbol relied on the retrieved SINR in the phase 3.2.2, since $E_s = 10^{\frac{1}{10}(SINR_{dB}+Noc_{dB})}$.
- Channel model: AWGN.

RF Receiver

Based on the Simulink implementation, stated in Figure 3.10, this section performed the simulation of the unified model to recover the test LTE waveform and its sampling period. After executing the band-limiting filtering and then passing the signal through the channel—underneath the proposed propagation model and AWGN instance—the LTE waveform was demodulated and reach the DC to remove the DC offset. At this point, the ending step encompassed the frame simulation to analyze the network throughput.

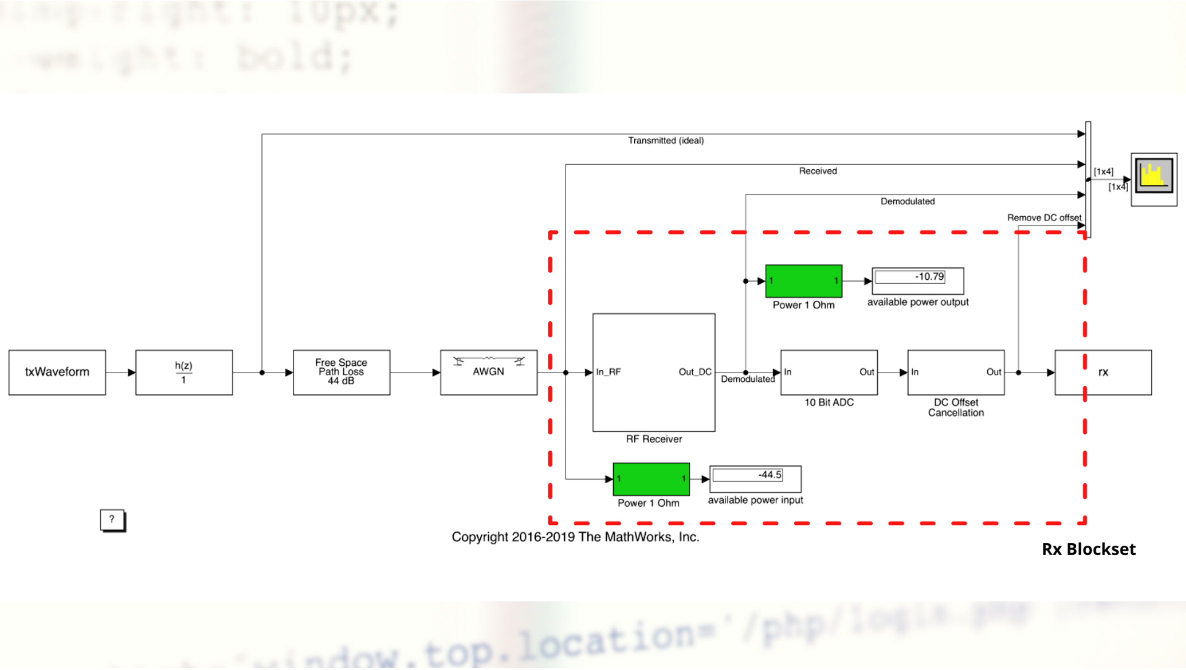


Figure 3.10: Assessed Rural Mobile Network in Colombia

The Blockset Testbench simulated five frames, done in two steps. The first frame should foresee the band-limiting filter's group delay; then, the length of the early frame increased slightly. The subsequent frames were maintained during the filter state. Finally, the EVM block measured the difference between the actual received symbols and the ideal ones—given in percentage RMS units—under the ETSI recommendation of a maximum of 8% when the constellation is 64-QAM [2].

Chapter 4

Results

4.1 Propagation Modelling

Doubtlessly, by setting forth the differences between the stated models in chapter 3, it is possible to determine the efficiency of propagation characterization and, therefore, determine the channel parameters estimation without high error values, such as Path Loss Exponent (n) and Shadowing Deviation (σ) of the assessed environment. With the collected data in the Measurement Campaign, Figure 4.1 displays the data fitting by considering the models in Table 3.3.

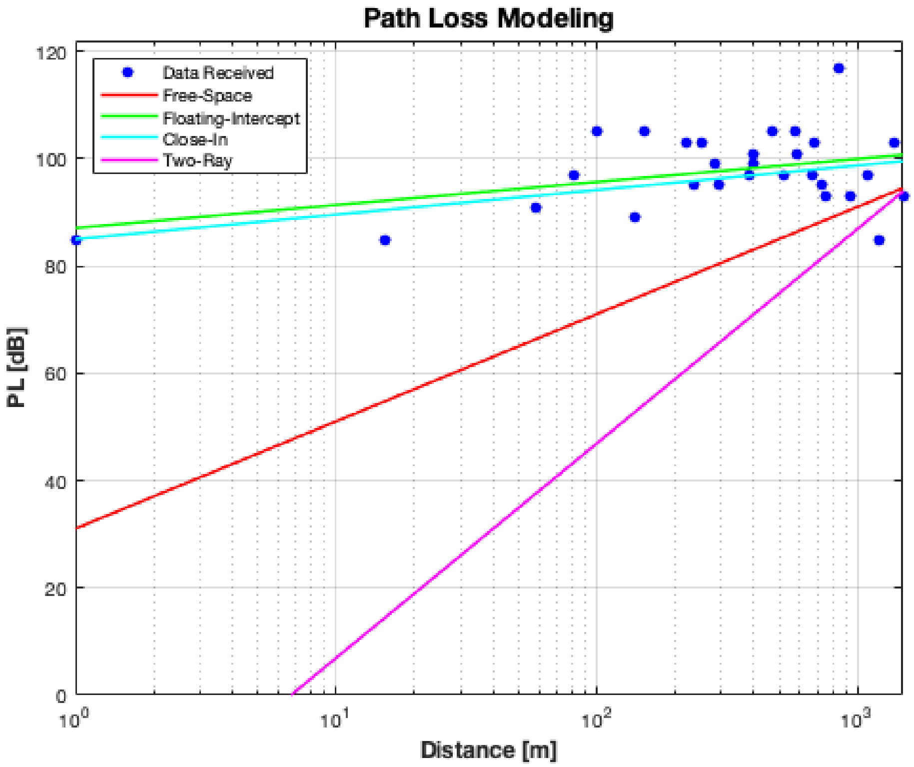


Figure 4.1: Data Fitting and Path Loss Modelling

From the results shown in Figure 4.1, the models *Close-In* (CI) and *Floating-Intercept* (FI) are the best-fitting ones. For both cases, the estimated PLE provides the information of the interaction between the transmitter and each receiver. Those value are presented in 4.1 by using the MATLAB algorithm stated in chapter A. Recalling that the path loss includes all of the possible elements of loss associated with any obstacle [90].

Table 4.1: Propagation Parameters of the Assessed Zone

Parameter	Value
$\mathbf{n_{FI}}$	4.2941
$\mathbf{n_{CI}}$	4.5792
σ	6.5725

By crossing the information outlined in Table 4.1 and 3.2 for the proposed scenario, there is no remarkable difference between the estimated and the theoretical PLE values, which Long-distance model was embraced in both chosen models. Thereby, a commitment has arisen to carry out in-depth analysis through the error calculation. To this end, Figure 4.2 shows the Root Mean Square Error (RMSE) of the propagation model based on the L_50 reference (or FI).

The RMSE furnishes the standard deviation of the prediction errors or residuals by linear regression estimation. In fewer words, RMSE is the measure of how spread out these residuals are. A lower error pattern should be adopted to sketch the simulated LTE network coverage area for the chosen rural scenario. Free-Space and Two-Ray patterns own the highest RMSE values, and in contrast, the CI holds the lowest one. As a result, the rural LTE simulation would lie on the CI propagation model.

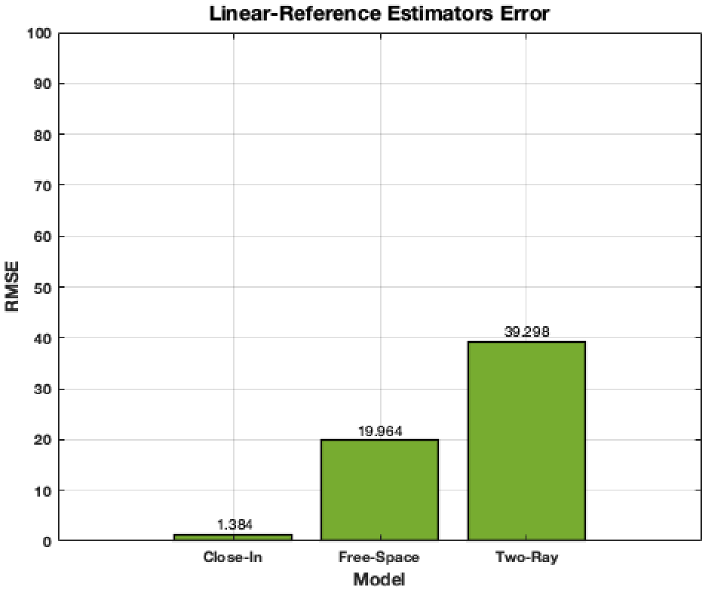


Figure 4.2: Error on Path Loss Modelling

4.2 Rural LTE Network Simulation

The CI model seems to characterize the carrier's behavior outstandingly whether an LTE network was deployed in both study cases. Nevertheless, there is a need to identify apriori the likely not-spots by employing the simulation strategy, where MATLAB appears to be the most helpful tool to shed light on this aim, particularly employing its RF Toolbox.

To grasp the scope of located simulation underneath the chosen propagation mode, the used algorithm leverage the MATLAB Antenna Toolbox to hand over the coverage map, bounded by the location of the BS and two test receivers. The receivers represent the places in which the network displays the best and the worst RSSI, respectively.

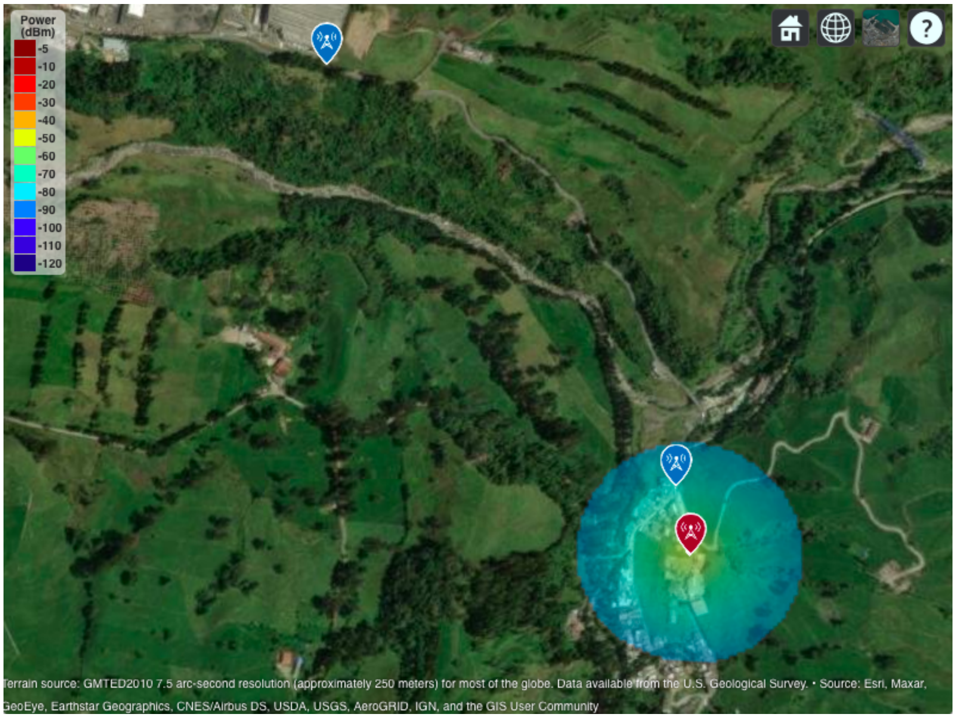


Figure 4.3: Estimated Coverage Map Beneath the Considered Propagation Model

Figure 4.3 outlines the estimation of received given by the transmitter point. Aside from the signal attenuation that relies on the farness distance, there is a further conception over the uneven coverage of the network since other involved patterns such as shadowing and fading. To incur in noise characterization, Figure 4.4 reflects the behavior of the SINR while the user is moving away from the BS.

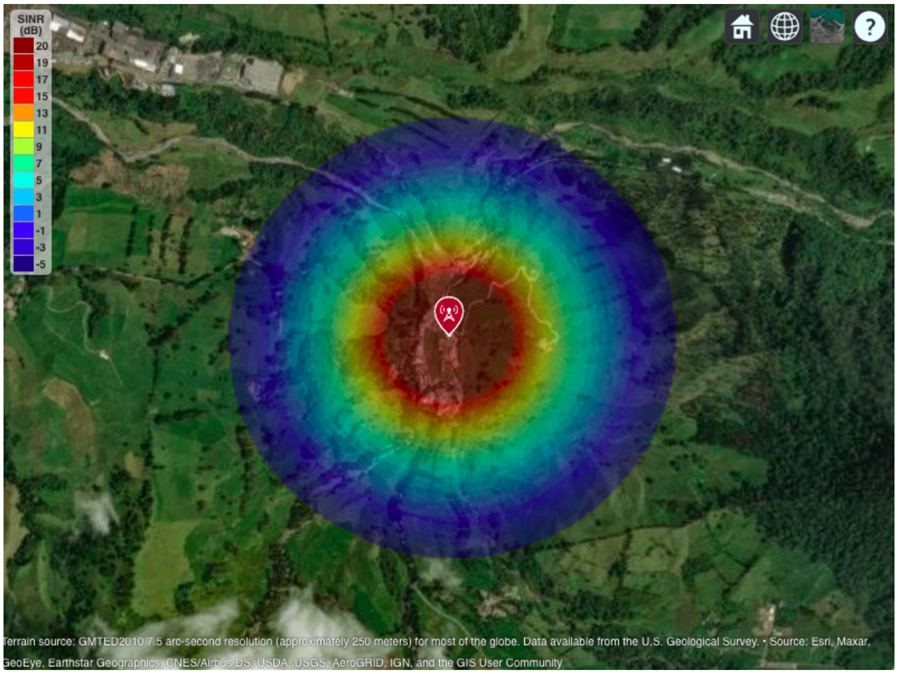
As mentioned earlier, the simulation is suitable for going further inside this stage to shed light on the likely construction of a physical UAV-based LTE network. To this end, it is feasible to meet the current channel parameters beforehand and then undertaking an LTE model thoroughly by relying on the formulated algorithm in the previous chapter of this book. Therefore, Table 4.2 displays the SINR in both test receivers, which will be engaging for the next steps of the simulation.

Table 4.2: Assessed SINR for Both Test Receivers

$\mathrm{R_x}$	**SINR** [dB]
Min.	64.2320
Max.	83.7031

4.2.1 Algorithm Outcomes and Predictions

Under the eagerness to obtain an optimum SINR to consider in future UAV-based LTE network rollout, it is convenient to maximize the information received by the users in the countryside and, therefore, to avoid the derived shortcomings because of the lower coverage since



Terrain source: GMTED2010 7.5 arc-second resolution (approximately 250 meters) for most of the globe. Data available from the U.S. Geological Survey. • Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 4.4: Consideration of SINR in the Test Zone

the presence of uneven links with the farness BS.

In chapter 3 was introduced the blocks diagram that follows the LTE receiver by an operative simulation, namely the system performance, which may be determined by the Error Vector Magnitude (EVM) measure at the output of the demodulator block. Bringing back the SINR results—stated in Table 4.2—of the studied channel in the proposed Colombia's rural settlement, the main aim is to analyze both test receivers' efficiency and predicting the reception error of a probable user in the aforementioned zone.

SINR is the key parameter in calculating the system performance in an AWGN channel [90]. Consequently, the recovered information of Max. and Min. Rx would arrange in the Filtering and Channel blocks. To best sketch out the achieved results by the MATLAB algorithm, it is crucial to broader analyze both cases, specifically as follows.

Greatest Coverage Receiver Simulation

In the first instance, the values of EVM will be the lowest seemingly, since the best coverage of the network fuels the receiver, supported by the best SINR. Figure 4.5 exhibits four recovered signals from the simulation to stand out the performance of the LTE system and to envision the signal's delivery, which is heading through the manifold conforming blocks.

The foregoing Figure 4.5 establishes the received spectrum of the waveform of the OFDM carrier by comparing the following signals: Transmitted (yellow), received (blue), demodulated (orange), and removed DC offset (green). There are various similarities among input and output information in the receptor, given by the transmitted and demodulated signals. Regardless of the likely variations in the AWGN block, the signal outside the demodulator almost follows the ideal one, overcoming the group delay met by the Filtering stage in the first frame.

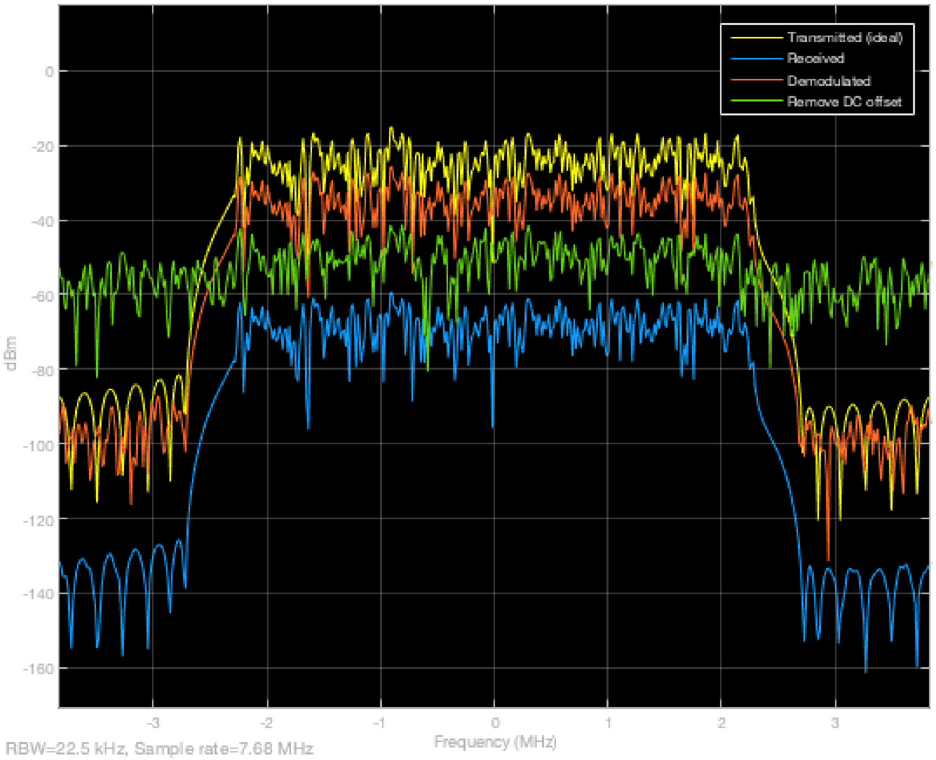


Figure 4.5: Spectrum of LTE Signals in Max. Rx Case

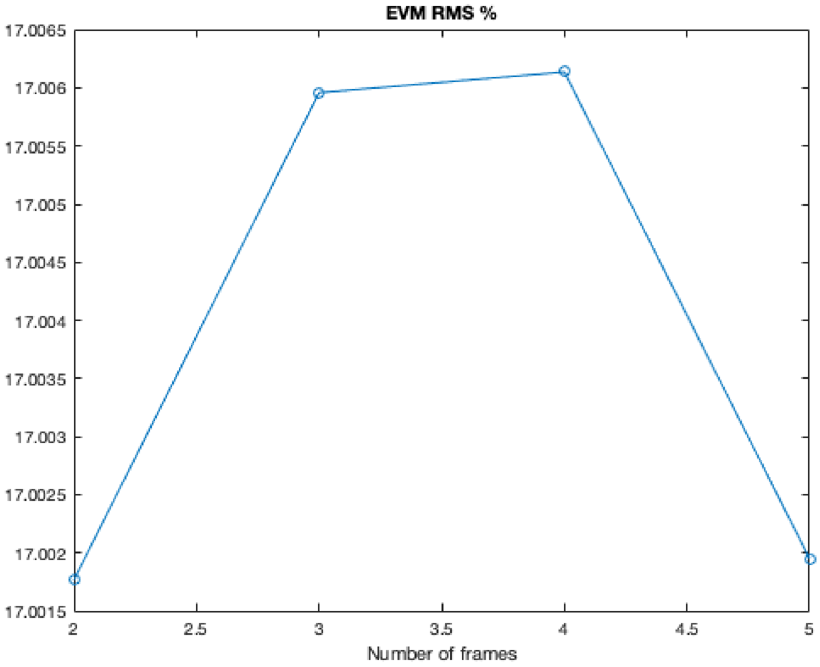


Figure 4.6: Percentage of EVM RMS in Max. Rx Case

The EVM furnishes the difference between the related symbol to the signals mentioned above to approach the system's efficiency by error analysis. In this particular case, the EVM would tend to minimize as the passing number of frames would increase. In terms of the percentage of EVM RMS—stated in Figure 4.6—a variation of almost 17% is envisaged by the LTE receiver. Therefore, this value reflects the probability of error in transmitting several frames for the investigated rural settlement in Colombia.

Weakest Coverage Receiver Simulation

Figure 4.7 displays the LTE waveform's spectrum for the realized lower RSSI receptor. In this instance, the power gap between the transmitter signal and the demodulated one is noticeable without introducing a likely attenuation given by the DC offset block. Another important aspect is the limitation of lateral ripples in the stop-band frequencies, where the noise can incur in these bands.

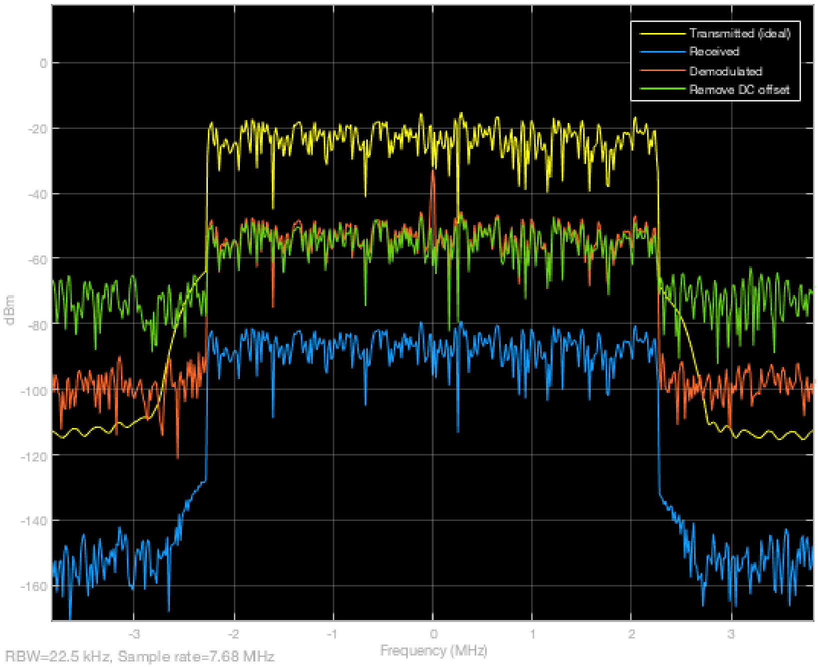


Figure 4.7: Spectrum of LTE Signals in Min. Rx Case

Regarding the EVM measures—set forth in Figure 4.8—in the minimum covered receptor, several interferences are stuck in the link with the BS site since the uneven relief triggers a lower SINR index. Thereby, the upsurge of the percentage of EVM RMS is notable as long as the number of frames rises up. To curb the weak reception by the insufficient coverage—perceived by the users—the aim to design the Link Budget appears to be the first step to approaches the minimization of probability error.

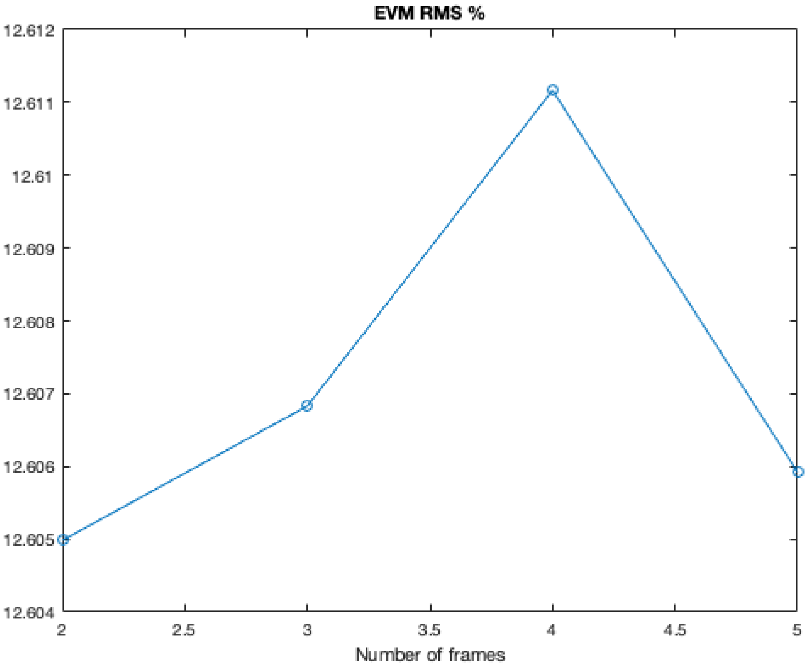


Figure 4.8: Percentage of EVM RMS in Min. Rx Case

Chapter 5

Discussion

Beneath the lack of connectivity standards in the countryside, several technologies have emerged to support optimal coverage in the context mentioned earlier. The research approaches—stated in chapter 2—seem suitable to establish optimal and steady links, improving the QoS of the affordable countryside's networks. Furthermore, by in-depth analysis of the trending of thesis seed—employing a reliable database such as Scopus—the relevance of the proposed hypothesis can further be assessed, as it was expressed in chapter 1.

Nowadays, complete Internet access to rural zones may be paradoxical due to the lack of efforts to deploy suitable mobile network infrastructure. However, data demand has grown recently since many rural inhabitants consider using technology to improve their quality of life by implementing trending technologies, such as IoT. Although Latin American countries have recently envisaged closing the connectivity gap, there are remote geographical zones where the not-spots are a significant challenge to governments because they strive to outpace inequality under the insight of fully-fledged coverage.

Evoking the proposed study countries cases in this book—Mexico and Colombia—which have economically and technologically developed in the last decade, the connectivity gaps are noticeable yet. Therefore, implementing alternative and efficient solutions—as listed in section 2—approach hooking the peripheral population up by a reliable deployment.

The COVID-19 pandemic has accelerated the reshaping of a noteworthy need for connectivity since most of our performed activities leverage digitalization growth to attempt affordability and readily access. Although several rural populations remain fully offline, the recent efforts to stimulate new steady links have triggered new opportunities to access online education, remote employment, and health and sanitation advice.

By establishing statistics that best drawn the mentioned panorama, the aforementioned novel method encourages further access to ICT and lays on the target of providing affordable access to the Internet in developed countries, which in turn considers rural and geographically remote populations. Hence, solutions such as UAVs, HAPS/LAPS, and LEO satellites have arisen for the most cost-effective bargaining. However, there has been a comprehensively studied UAS scope in communication in this book because its efficient maneuverability can encompass the coverage problem through a solid construction of either GBS or FANET approaches.

The current thesis project has summarized some strategies that seek to strengthen connectivity in rural environments, especially for Latin American countries, besides introducing a novel network framework based on UAVs. After analyzing the obtained data in the measurement campaign, it is possible to conclude that there are manifold shortcomings in the stated model—because the obtained EVM exceeds the standardized of 8%—due to the limitations on the accuracy of the used devices. Nevertheless, this approach can become an outstanding opportunity to develop the AGC research by considering higher-level simulations and even trustworthy LTE deployments to spur a fully connected countryside in Latin America and the entire world.

Appendix A

Data Acquisition Algorithm

```
/* Experimental Stage V1.1
March, 2021

This version aims to catch the real-time RSSI and BER parameters of the current MNO channel.
To avoid the aggregation of aditional shields, the measurements will be uploaded to ThingSpeak server: https://thingspeak.com/channels/1316280/private_show

Webgraphy:
1. https://lastminuteengineers.com/sim900-gsm-shield-arduino-tutorial/
2. https://how2electronics.com/send-gsm-sim800-900-gprs-data-thingspeak-arduino/
3. https://www.youtube.com/watch?v=irI11IBUojs
4. https://m2msupport.net/m2msupport/atcstt-satrt-task-and-set-apn-username-and-password/
5. https://docs.rs-online.com/5931/0900766b80bec52c.pdf
-----------------------------------------------------------------------
*/

// Allowing the module software trigger

void SIM900power()
{
  pinMode(9, OUTPUT);
  digitalWrite(9,LOW);
  delay(1000);
  digitalWrite(9,HIGH);
  delay(2000);
  digitalWrite(9,LOW);
  delay(3000);
}

#include <SoftwareSerial.h>

String ATRes, tempRSSI, tempBER;
int temp,rssi;
float ber;
```

```

char inSerial[1024];

//Create software serial object to communicate with SIM900
SoftwareSerial mySerial(7, 8); //SIM900 Tx & Rx is connected to Arduino #7 & #8

void setup()
{
  SIM900power();

  delay(1000);

  //Begin serial communication with Arduino and Arduino IDE (Serial Monitor)
  Serial.begin(19200);

  //Begin serial communication with Arduino and SIM900
  mySerial.begin(19200);

  Serial.println("Initializing...");
  delay(1000);

  mySerial.println("AT"); //Handshaking with SIM900
  //updateSerial();
  showSerialData();
  mySerial.println("AT+CSQ"); //Signal quality test, value range is 0-31 , 31 is the best
  //updateSerial();
  showSerialData();
  mySerial.println("AT+CCID"); //Read SIM information to confirm whether the SIM is plugged
  //updateSerial();
  showSerialData();
  mySerial.println("AT+CREG?"); //Check whether it has registered in the network
  //updateSerial();
  showSerialData();
}

void loop(){

  mySerial.println("AT+CSQ");
  //showSerialData();
  delay(1000);

  if (Serial.available()>0){
    mySerial.write(Serial.read());
  }

  if(mySerial.available()>0){
    /*
    int i = 0;
    while(mySerial.available()>0){
```

```
     inSerial[i] = (mySerial.read());
     i++;
     Serial.println(i);
     Serial.println(inSerial[i]);
     delay(500);
   }
   inSerial[i] = '\0';
   */
   //Serial.println(inSerial[45]);
   ATRes = mySerial.readString();
 }
  //Serial.println(ATRes);
  tempRSSI = ATRes.substring(ATRes.length()-12,ATRes.length()-10);
  tempBER = ATRes.substring(ATRes.length()-9,ATRes.length()-8);

  Serial.println("RXLEV: ");
  Serial.print(tempRSSI);
  Serial.println("\n");

  Serial.println("RXQUAL: ");
  Serial.print(tempBER);
  Serial.println("\n");

  rssi = (2*(tempRSSI.toInt()))-113;
  Serial.println("RSSI [dBm] = ");
  Serial.print(rssi);
  Serial.println("\n");

  temp = tempBER.toInt();
  switch (temp) {
   case 0:
     ber= 0.14;
     break;
   case 1:
     ber= 0.28;
     break;
   case 2:
     ber= 0.57;
     break;
   case 3:
     ber= 1.13;
     break;
   case 4:
     ber= 2.26;
     break;
   case 5:
     ber= 4.53;
     break;
   case 6:
     ber= 9.05;
     break;
   case 7:
     ber= 18.10;
     break;
```

```
    default:
      ber = 100;
      break;
    }

   Serial.println("BER [%] = ");
   Serial.print(ber);
   Serial.println("\n");

   delay (3000);

  //Connection with the Thinkspeak Server
  mySerial.println("AT+CIPSTATUS");
  delay(2000);

  mySerial.println("AT+CIPMUX=0");
  delay(3000);
  showSerialData();

  mySerial.println("AT+CSTT=\"internet.comcel.com.co\",\"comcelweb\",\"comcelweb\"");
  delay(1000);
  showSerialData();

  mySerial.println("AT+CIICR");
  delay(3000);
  showSerialData();

  mySerial.println("AT+CIFSR");
  delay(2000);
  showSerialData();

  mySerial.println("AT+CIPSPRT=0");
  delay(3000);
  showSerialData();

  mySerial.println("AT+CIPSTART=\"TCP\",\"api.thingspeak.com\",\"80\"");
  delay(6000);
  showSerialData();

  mySerial.println("AT+CIPSEND");//begin send data to remote server
  delay(4000);
  showSerialData();

  String datos="GET https://api.thingspeak.com/update?api_key=ZSYGYB2I6CC3DKFU&field1=" + String(rssi) + "&field2="+ String(ber);
  mySerial.println(datos);//begin send data to remote server
  delay(4000);
  showSerialData();

  mySerial.println((char)26);//sending
  delay(5000);//waitting for reply, important! the time is base on the condition of internet
  mySerial.println();
```

```
  showSerialData();

  mySerial.println("AT+CIPSHUT");//close the connection
  delay(5000);
  showSerialData();

}

void showSerialData(){
  while(mySerial.available()!=0){
    Serial.write(mySerial.read());
  }
  delay(3000);
}
```

Appendix B

Propagation Modelling Code

```
%% Experimental Stage
%% Substage: Propagation Model
% Diego Fernando Cabrera Castellanos
% April, 2021

clc, clear all, close all

%% A.  Data Collection

data = readtable("Data.xlsx",'Sheet','COORDINATES2');

lat = data.LATITUDE;
latTx = lat(1);
lat = lat(2:end);

long = data.LONGITUDE;
longTx = long(1);
long = long(2:end);

rsrp = data.RSSI2;
rsrp = rsrp(2:end);

% A. 1. Measures Georeferencing
figure;
gx = geobubble(lat,long,rsrp);
gx.Basemap= 'satellite';
gx.Title = 'Assessed Zone: Colombia';
gx.BubbleWidthRange = [5 15];
gx.SizeLegendTitle = 'RSRP';

% A.2. RSRP: Reference Signal Received Power [dB]
power = rsrp-30;

% A.3. Vector of distances from the origin (Tx) to each measure point (Rx)
d = data.d;
d = d(2:end);
[d,pos] = sort(d);
power = power(pos);
```

```

%% B. Propagations Models

% B.1. Parameters Delimitation
% References
d0 = d(1);
P0 = power(1);

% Height [m]
hT = 30;
hR = 1.5;

% Tranmission Frequency [Hz]
f = 850*1e6; % Band 5 MNO: Claro Movil Colombia

% Wavelength [m]
c = 299702547; %Light speed
lambda = c/f;

% B.2. PLE Modeling
% 1) Free-Space Model
PlFS = fspl(d,lambda);

% 2) Floating-Intercept Model (Linear Regression)
lm = fitlm(log10(d),power);
% Estimation of received power through linearization method: Y = aX+b
B = lm.Coefficients.Estimate(1);
A = lm.Coefficients.Estimate(2);
% Goodness of Fit
rsq = lm.Rsquared.Ordinary;
nLIN = abs(A);
% Estimation of Path Loss
PlLIN = A*log10(d)+B;
PlLIN = abs(PlLIN);

% 3) Close-In Model (MLE Estimation)
MLE = mle(abs(power),’distribution’,’logn’);
nMLE = MLE(1);
% Estimation of Path Loss
%PlMLE = fspl(d0,lambda)+10*nMLE*log10(d/d0);
PlMLE = abs(P0)+nMLE*log10(d/d0);

% 4) Two-Ray Model
PlTR = 40*log10(d)-20*log10(hT*hR);

% 4) Comparison of Modeling
figure;
semilogx(d,abs(power),’ob’,’MarkerSize’,5,’MarkerFaceColor’,’b’);
hold on;
semilogx(d,PlFS,’r’,’LineWidth’,1.5);
semilogx(d,PlLIN,’g’,’LineWidth’,1.5);
semilogx(d,PlMLE,’c’,’LineWidth’,1.5);
semilogx(d,PlTR,’m’,’LineWidth’,1.5);
hold off;
```

```
grid on;
ylim([0 max(abs(power))+5]);
title('Path Loss Modeling','FontSize',14,'FontWeight','bold');
xlabel('Distance [m]','FontSize',12,'FontWeight','bold');
ylabel('PL [dB]','FontSize',12,'FontWeight','bold');
legend('Data Received','Free-Space', 'Floating-Intercept',...
    'Close-In','Two-Ray');

% B.3. Scattering by Shadowing
% 1) SD of Floating-Intercept Model
sdLIN = std(PlLIN);

% 2) SD using MLE for Close-In Model
N = length(power);
vMLE = power-P0;
vMLE = vMLE +(nMLE*log10(d./d0));
vMLE = vMLE.^2;
vMLE = sum(vMLE);
vMLE = (1/N)*vMLE;
sdMLE = sqrt(vMLE);

% B.4. Estimations Error
% Linear Reference MSE
e = [sqrt(immse(PlLIN,PlMLE)) sqrt(immse(PlLIN,PlFS)) ...
    sqrt(immse(PlLIN,PlTR))];

figure;
hB = bar(e,'FaceColor',[0.4660 0.6740 0.1880],'LineWidth',1.2);
grid on;
ax = gca;
ax.FontWeight = 'bold';
ax.XTickLabel = categorical({'Close-In','Free-Space','Two-Ray'});
h = [];
for i=1:length(hB)
  h=[h text(hB(i).XData+hB(i).XOffset,hB(i).YData,num2str(hB(i).YData.','%.3f'), ...
                          'VerticalAlignment','bottom','horizontalalign','center')];
end
title('Linear-Reference Estimators Error','FontSize',14,'FontWeight','bold');
xlabel('Model','FontSize',12,'FontWeight','bold');
ylabel('RMSE','FontSize',12,'FontWeight','bold');
ylim([0 100]);


%% C. Coverage and SINR Determination
% The following procedures are furnished by Communication Toolbox of MATLAB

% C.1. Propagation Model Stablishment
pm = propagationModel('close-in',...
    'PathLossExponent',nMLE,...
    'Sigma',sdMLE);
```

```

% C.2 Transmitter Site
% In a macro-cell BS is 20-69 W at the antenna connector (LTE)
tx = txsite('Name',"BS",...
       'Latitude',latTx, ...
       'Longitude',longTx, ...
       'TransmitterFrequency',f,...
       'TransmitterPower',60,...
       'AntennaHeight',hT);

% C.3 Receiver Sites
powerMin = min(rsrp);
powerMax = max(rsrp);

posMin = 25;
posMax = 17;

rxMin = rxsite('Name',"RxMin",...
       'Latitude',lat(posMin),...
       'Longitude',long(posMin), ...
       'AntennaHeight',hR,...
       'ReceiverSensitivity',powerMin);

rxMax = rxsite('Name',"RxMax",...
       'Latitude',lat(posMax),...
       'Longitude',long(posMax),...
       'AntennaHeight',hR,...
       'ReceiverSensitivity',powerMin);

% C.4 Coverage Map

coverage(tx,rxMax,...
    'PropagationModel',pm,...
    'MaxRange',1500,...
    'SignalStrengths',powerMin:0.5:powerMax);


coverage(tx,rxMin,...
    'PropagationModel',pm,...
    'MaxRange',1500,...
    'SignalStrengths',powerMin:0.5:powerMax);

% C.5. SINR furnished to each Rx
SINR = [sinr(rxMin,tx),sinr(rxMax,tx)];
```

Appendix C

LTE Receiver Simulation Code

```
%% Experimental Stage
%% Substage: Simulation
% Diego Fernando Cabrera Castellanos
% April, 2021

clc, clear all, close all

%% Block: LTE RF Receiver
% Modeling and Testing

% Source: MATLAB Example:
% https://la.mathworks.com/help/lte/ug/modeling-and-testing-an-lte-rf-receiver.html

% Block Diagram
%
% |LTE Wavef|-> |Filtering|-> |Channel|-> |RF Receiv|-> |EVM|
%
%

%% A. LTE Waveform

% Configuration TS 36.101 25 REs (5 MHz), 64-QAM, full allocation
rmc = lteRMCDL('R.6'); % Downlink reference measurement channel configuration
rmc.OCNGPDSCHEnable = 'On'; % Enable PDSCH OCNG

% Create eNodeB transmission with fixed PDSCH data
rng(2);                  % Fixed random seed (arbitrary)
data = randi([0 1], sum(rmc.PDSCH.TrBlkSizes),1);
% rmc.PDSCH.TrBlkSizes: Transport block sizes for 1 or 2 codewords used in the transmission

% Generate 1 frame, to be repeated to simulate a total of N frames
```

```matlab
[tx, ~, info] = lteRMCDLTool(rmc, data); % Downlink RMC waveform generation
% info: structure containing information about the OFDM modulated waveform
% tx: T-by-P matrix where T is the number of time domain samples and P is the number of antennas

% Calculate the sampling period and the length of the frame.
SamplePeriod = 1/info.SamplingRate;
FrameLength = length(tx);

%% B. Filtering and Channel

% Band limiting interpolation filter
FiltOrd = 32;
% Parks-McClellan optimal equiripple FIR filter design
h = firpm(FiltOrd,[0 2.25e6*2*SamplePeriod 2.7e6*2*SamplePeriod 1],[1 1 0 0]);
FilterDelaySamples = FiltOrd/2; % filter group delay

% Propagation model

SNRdB = 57; %Suggested Es/Noc for the simulation
%SNRdB = 64.2320; % Es/Noc in dB for RxMin - Simulated in PM Substage
%SNRdB = 83.7031; % Es/Noc in dB for RxMax - Simulated in PM Substage
NocdBm = -98;                % Noc in dBm/15kHz
NocdBW = NocdBm - 30;        % Noc in dBW/15kHz57
SNR = 10^(SNRdB/10);         % linear Es/Noc
Es = SNR*(10^(NocdBW/10));   % linear Es per RE
FFTLength = info.Nfft;
SymbolPower = Es/double(FFTLength);

% Number of simulation frames N>=1
N = 5;

% Preallocate vectors for results for N-1 frames
% EVM is not measured in the first frame to avoid transient effects
evmpeak = zeros(N-1,1);    % Preallocation for results
evmrms = zeros(N-1,1);     % Preallocation for results

%% 3. RF Receiver in Simulink
model = 'RFLTEReceiverModel';
disp('Starting Simulink');
open_system(model);

%% 4. Frame Simulation

% Generate test data for RF receiver
time = (0:FrameLength+FilterDelaySamples)*SamplePeriod;
% Append to the end of the frame enough samples to compensate for the delay
% of the filter
txWaveform = timeseries([tx; tx(1:FilterDelaySamples+1)],time);

% Simulate RF Blockset model of RF RX
```

```
set_param(model, 'LoadInitialState', 'off');
disp('Simulating LTE frame 1 ...');
sim(model, time(end));
% Save the final state of the model in xInitial for next frame processing
xInitial = xFinal;

% Synchronize to received waveform
Offset = lteDLFrameOffset(rmc,squeeze(rx),'TestEVM');
% In this case Offset = FilterDelaySamples therefore the following
% frames do not require synchronization

% Load state after execution of previous frame. Since we are repeating the
% same frame the model state will be the same after every frame execution.
set_param(model, 'LoadInitialState', 'on', 'InitialState','xInitial');
% Modify input vector to take into account the delay of the bandlimiting
% filter
RepeatFrame = [tx(FilterDelaySamples+1:end); tx(1:FilterDelaySamples+1)];
EVMalg.EnablePlotting = 'Off';
cec.PilotAverage = 'TestEVM';

for n = 2:N % for all remaining frames
    % Generate data
    time = ( (n-1)*FrameLength+(0:FrameLength) + FilterDelaySamples)*
   SamplePeriod;
    txWaveform = timeseries(RepeatFrame,time);

    % Execute Simulink RF Blockset testbench
    disp(['Simulating LTE frame ',num2str(n),' ...']);
    sim(model, time(end));
    xInitial = xFinal; % Save model state

    % Compute and display EVM measurements
    evmmeas = hPDSCHEVM(rmc,cec,squeeze(rx),EVMalg);
    evmpeak(n-1) = evmmeas.Peak;
    evmrms(n-1) = evmmeas.RMS;
end

%% 5. Measured EVM

figure;
plot((2:N), 100*evmpeak,'o-')
title('EVM peak %');
xlabel('Number of frames');
figure;
plot((2:N), 100*evmrms,'o-');
title('EVM RMS %');
xlabel('Number of frames');

% Ending Simulation
bdclose(model);
clear([model,'_acc']);
```

Bibliography

[1] Etsi technical specificiation ts 136.101. Tech. rep., ETSI 3GPP, 2017.

[2] Etsi technical specificiation ts 136.104. Tech. rep., ETSI 3GPP, 2017.

[3] Uas traffic management architecture. Tech. rep., GUTMA, 2017.

[4] Designing utm for global success. Tech. rep., GUTMA, 2020.

[5] Lte aerial profile v1.00. Tech. rep., GSMA, GUTMA, 2020.

[6] Send receive sms & call with sim900 gsm shield & arduino. www.lastminuteengineers.com/sim900-gsm-shield-arduino-tutorial, 2020.

[7] 3GPP. 3gpp regulation for uas-uav. https://www.3gpp.org/uas-uav, 2019.

[8] Akpakwu, G. A., Silva, B. J., Hancke, G. P., and Abu-Mahfouz, A. M. A survey on 5g networks for the internet of things: Communication technologies and challenges. *IEEE Access 6* (2017), 3619–3647. Cited By :147.

[9] Al-Hourani, A., and Gomez, K. Modeling cellular-to-uav path-loss for suburban environments. *IEEE Wireless Communications Letters 7*, 1 (2018), 82–85.

[10] Alam, M. S., Kurt, G. K., Yanikomeroglu, H., Zhu, P., and Đào, N. D. High altitude platform station based super macro base station constellations. *IEEE Communications Magazine 59*, 1 (2021), 103–109.

[11] Alastair Westgarth. Saying goodbye to Loon. https://medium.com/loon-for-all/loon-draft-c3fcebc11f3f/, 2021.

[12] Almalki, F. A., and Angelides, M. C. A machine learning approach to evolving an optimal propagation model for last mile connectivity using low altitude platforms. *Computer Communications 142-143* (2019), 9–33.

[13] Amine, L. M., Adil, E. B., and Aawatif, P. H. Toward enhancing connectivity through tvws in outdoor rural isolated environment. In *2017 Sensors Networks Smart and Emerging Technologies (SENSET)* (Sep. 2017), pp. 1–4.

[14] Amorosi, L., Chiaraviglio, L., D'Andreagiovanni, F., and Blefari-Melazzi, N. Energy-efficient mission planning of uavs for 5g coverage in rural zones. In *2018 IEEE International Conference on Environmental Engineering, EE 2018 - Proceedings* (2018).

[15] ARAUJO, M., EKENBERG, L., AND CONFRARIA, J. Satellite backhaul for macro-cells, as an alternative to optical fibre, to close the digital divide. In *IEEE Wireless Communications and Networking Conference, WCNC* (2019), vol. 2019-April.

[16] ARAÚJO, M., EKENBERG, L., AND CONFRARIA, J. Rural networks cost comparison between 5g (mobile) and fttx (fixed) scenarios. In *2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)* (Sep. 2018), pp. 259–264.

[17] ARDUINO. What is arduino? www.arduino.cc/en/Guide/Introduction, 2018.

[18] ARIFIN, M. A., AND KHAMSAH, N. M. N. A case study in user capacity planning for low earth orbit communication satellite. In *ICARES 2018 - Proceedings of the 2018 IEEE International Conference on Aerospace Electronics and Remote Sensing Technology* (2018).

[19] ARPAIO, M. J., VITUCCI, E. M., BARBIROLI, M., DEGLI-ESPOSTI, V., MASOTTI, D., AND FUSCHINI, F. Narrowband characteristics of air-to-ground propagation for uav assisted networks in urban environments by means of fast ray-launching simulations. In *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)* (2020).

[20] ARUM, S. C., GRACE, D., AND MITCHELL, P. D. A review of wireless communication using high-altitude platforms for extended coverage and capacity. *Computer Communications 157* (2020), 232–256.

[21] BASU, P., REDI, J., AND SHURBANOV, V. Coordinated flocking of uavs for improved connectivity of mobile ground nodes. In *Proceedings - IEEE Military Communications Conference MILCOM* (2004), vol. 3, pp. 1628–1634.

[22] BECKER, D., FIEBIG, U., AND SCHALK, L. Wideband channel measurements and first findings for low altitude drone-to-drone links in an urban scenario. In *2020 14th European Conference on Antennas and Propagation (EuCAP)* (2020).

[23] BROWN, T., ARGROW, B., FREW, E., DIXON, C., HENKEL, D., ELSTON, J., AND GATES, H. *Experiments using small unmanned aircraft to augment a mobile ad hoc network*, vol. 9780521895842 of *Emerging Technologies in Wireless LANs: Theory, Design, and Deployment*. 2007, pp. 695–718.

[24] CARRILLO, D., AND SEKI, J. Rural area deployment of internet of things connectivity: Lte and lorawan case study. In *Proceedings of the 2017 IEEE 24th International Congress on Electronics, Electrical Engineering and Computing, INTERCON 2017* (2017).

[25] CERASOLI, C. An analysis of unmanned airborne vehicle relay coverage in urban environments. In *Proceedings - IEEE Military Communications Conference MILCOM* (2007).

[26] CHANDRASHEKAR, K., DEKHORDI, M. R., AND BARAS, J. S. Providing full connectivity in large ad-hoc networks by dynamic placement of aerial platforms. In *Proceedings - IEEE Military Communications Conference MILCOM* (2004), vol. 3, pp. 1429–1436.

[27] CHEN, J. Network analysis based on 2/4g common coverage research in rural area. In *2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData)* (July 2018), pp. 295–300.

[28] CHEN, Y., ZHANG, H., AND XU, M. The coverage problem in uav network: A survey. In *5th International Conference on Computing Communication and Networking Technologies, ICCCNT 2014* (2014).

[29] CHIARAVIGLIO, L., AMOROSI, L., BLEFARI-MELAZZI, N., DELL'OLMO, P., LO MASTRO, A., NATALINO, C., AND MONTI, P. Minimum cost design of cellular networks in rural areas with uavs, optical rings, solar panels, and batteries. *IEEE Transactions on Green Communications and Networking 3*, 4 (2019), 901–918.

[30] DING, Y., LIU, H., AND CAO, X. An intelligent computation of coverage and capacity of base station in 3g mobile communications network. In *2008 International Conference on Computational Intelligence and Security* (Dec 2008), vol. 2, pp. 494–497.

[31] DOVIS, F., AND SELLONE, F. Increasing the capacity of existing terrestrial outdoor radio mobile systems by means of uav-hale platforms. In *IEEE Vehicular Technology Conference* (2000), vol. 3, pp. 2365–2369.

[32] FOTOUHI, A., QIANG, H., DING, M., HASSAN, M., GIORDANO, L. G., GARCIA-RODRIGUEZ, A., AND YUAN, J. Survey on uav cellular communications: Practical aspects, standardization advancements, regulation, and security challenges. *IEEE Communications Surveys and Tutorials 21*, 4 (2019), 3417–3442.

[33] GANESH, R., NING YANG, REGITZ, S., GIORDANO, A., AND FYE, D. Coverage considerations for cdma overlay of rural analog sites. In *2000 IEEE International Conference on Personal Wireless Communications. Conference Proceedings (Cat. No.00TH8488)* (Dec 2000), pp. 288–292.

[34] GATWAZA, W. W., AFULLO, T. J., AND SEWSUNKER, R. Characterization of rural traffic and evaluation of cellular protocols for fixed-mobile rural application. In *2004 IEEE Africon. 7th Africon Conference in Africa (IEEE Cat. No.04CH37590)* (Sep. 2004), vol. 1, pp. 245–250 Vol.1.

[35] GENARO CRUZ, GUILLAUME TOUCHARD, M. B. F. L. Enabling rural coverage: Regulatory and policy recommendations to foster mobile broadband coverage in developing countries. Tech. rep., GSMA Association, Squire Patton Boggs, 2018.

[36] GIAMBENE, G., ADDO, E. O., AND KOTA, S. 5g aerial component for iot support in remote rural areas. In *IEEE 5G World Forum, 5GWF 2019 - Conference Proceedings* (2019), pp. 572–577.

[37] GODDEMEIER, N., DANIEL, K., AND WIETFELD, C. Coverage evaluation of wireless networks for unmanned aerial systems. In *2010 IEEE Globecom Workshops, GC'10* (2010), pp. 1760–1765.

[38] GUO, W., DEVINE, C., AND WANG, S. Performance analysis of micro unmanned airborne communication relays for cellular networks. In *2014 9th International Symposium on Communication Systems, Networks and Digital Signal Processing, CSNDSP 2014* (2014), pp. 658–663.

[39] HAN, Z., SWINDLEHURST, A. L., AND LIU, K. J. R. Smart deployment/movement of unmanned air vehicle to improve connectivity in manet. In *IEEE Wireless Communications and Networking Conference, WCNC* (2006), vol. 1, pp. 252–257.

[40] HAN, Z., SWINDLEHURST, A. L., AND LIU, K. J. R. Optimization of manet connectivity via smart deployment/movement of unmanned air vehicles. *IEEE Transactions on Vehicular Technology 58*, 7 (2009), 3533–3546.

[41] HANDFORTH, C. Closing the coverage gap: How innovation can drive rural connectivity. Tech. rep., GSMA Association, 2019.

[42] HASAN, S., HEIMERL, K., HARRISON, K., ALI, K., ROBERTS, S., SAHAI, A., AND BREWER, E. Gsm whitespaces: An opportunity for rural cellular service. In *2014 IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN)* (2014), pp. 271–282.

[43] HAYAT, S., YANMAZ, E., AND MUZAFFAR, R. Survey on unmanned aerial vehicle networks for civil applications: A communications viewpoint. *IEEE Communications Surveys and Tutorials 18*, 4 (2016), 2624–2661.

[44] HOU, T., LIU, Y., SUN, X., SONG, Z., AND CHEN, Y. Non-orthogonal multiple access in multi-uav networks. In *IEEE Vehicular Technology Conference* (2019), vol. 2019-September.

[45] HUANG, L., ZHOU, Y., WANG, Y., HAN, X., SHI, J., AND CHEN, X. Advanced coverage optimization techniques for small cell clusters. *China Communications 12*, 8 (August 2015), 111–122.

[46] HUO, J., XU, Z., ZHANG, Y., AND SHAN, X. A uav mobile strategy in mobile ad hoc networks. In *2011 International Conference on Electronics, Communications and Control, ICECC 2011 - Proceedings* (2011), pp. 686–690.

[47] HYLAND, M. T., MULLINS, B. E., BALDWIN, R. O., AND TEMPLE, M. A. Simulation-based performance evaluation of mobile ad hoc routing protocols in a swarm of unmanned aerial vehicles. In *Proceedings - 21st International Conference on Advanced Information Networking and Applications Workshops/Symposia, AINAW'07* (2007), vol. 1, pp. 249–256.

[48] Ilcev, S. D., and Singh, A. Development of stratospheric communication platforms (scp) for rural applications. In *2004 IEEE Africon. 7th Africon Conference in Africa (IEEE Cat. No.04CH37590)* (Sep. 2004), vol. 1, pp. 233–238 Vol.1.

[49] Ilcev, S. D., and Singh, A. Development of stratospheric communication platforms (scp) for rural applications. In *2004 IEEE Africon. 7th Africon Conference in Africa (IEEE Cat. No.04CH37590)* (2004).

[50] INEGI. Datos de tics en hogares. https://www.inegi.org.mx/temas/ticshogares/, 2019.

[51] Institute, E. T. S. Gsm technical specification 05.08. Tech. rep., ETSI, 1996.

[52] Intelligence, G. Gsma mobile connectivity index. www.mobileconnectivityindex.com, 2019.

[53] Ioannou, N., Katsianis, D., and Varoutas, D. Comparative techno-economic evaluation of lte fixed wireless access, fttdp g.fast and fttc vdsl network deployment for providing 30mbps broadband services in rural areas. *Telecommunications Policy 44*, 3 (2020), 101875.

[54] Jimenez, J. G., Chiaraviglio, L., Amorosi, L., and Blefari-Melazzi, N. Multi-period mission planning of uavs for 5g coverage in rural areas: A heuristic approach. In *Proceedings of the 2018 9th International Conference on the Network of the Future, NOF 2018* (2018), pp. 52–59.

[55] Jiménez, J. G., Chiaraviglio, L., Amorosi, L., and Blefari-Melazzi, N. Multi-period mission planning of uavs for 5g coverage in rural areas: a heuristic approach. In *2018 9th International Conference on the Network of the Future (NOF)* (Nov 2018), pp. 52–59.

[56] Kalvin Bahia, A. D. The state of mobile internet connectivity 2020. Tech. rep., GSMA Intelligence, 2020.

[57] Kelif, J. Coverage and performance of stratospheric balloons wireless networks. In *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)* (Sep. 2016), pp. 1–6.

[58] Khawaja, W., Guvenc, I., Matolak, D. W., Fiebig, U., and Schneckenburger, N. A survey of air-to-ground propagation channel modeling for unmanned aerial vehicles. *IEEE Communications Surveys Tutorials 21*, 3 (2019), 2361–2391.

[59] Kim, H., Kim, Y., Park, P., Ahn, S., Jo, J., Park, S., and Park, C. Network coverage expansion in radio access network sharing. In *2017 Sixth International Conference on Future Generation Communication Technologies (FGCT)* (Aug 2017), pp. 1–5.

[60] Kovács, I. Z., Amorim, R., Nguyen, H. C., Wigard, J., and Mogensen, P. Interference analysis for uav connectivity over lte using aerial radio measurements. In *IEEE Vehicular Technology Conference* (2018), vol. 2017-September, pp. 1–6.

[61] Li, B., Fei, Z., and Zhang, Y. Uav communications for 5g and beyond: Recent advances and future trends. *IEEE Internet of Things Journal 6*, 2 (2019), 2241–2263.

[62] Loon LLC. The Loon Project. www.loon.com/, 2020.

[63] Lyu, J., Zeng, Y., Zhang, R., and Lim, T. J. Placement optimization of uav-mounted mobile base stations. *IEEE Communications Letters 21*, 3 (2017), 604–607.

[64] Manna, G. C., and Jharia, B. Mobile wimax coverage evaluation for rural areas of india. In *13th International Conference on Advanced Communication Technology (ICACT2011)* (Feb 2011), pp. 942–947.

[65] Mathworks. Antenna toolbox documentation. www.mathworks.com/help/antenna, 2021.

[66] Mathworks. Lte toolbox documentation. www.mathworks.com/help/lte, 2021.

[67] Mathworks. Thinkspeak documentation. www.mathworks.com/help/thingspeak, 2021.

[68] Mozaffari, M., Kasgari, A. T. Z., Saad, W., Bennis, M., and Debbah, M. Beyond 5g with uavs: Foundations of a 3d wireless cellular network. *IEEE Transactions on Wireless Communications 18*, 1 (2019), 357–372.

[69] Mozaffari, M., Saad, W., Bennis, M., and Debbah, M. Drone small cells in the clouds: design, deployment and performance analysis. In *2015 IEEE Global Communications Conference, GLOBECOM 2015* (2015).

[70] Mozaffari, M., Saad, W., Bennis, M., and Debbah, M. Efficient deployment of multiple unmanned aerial vehicles for optimal wireless coverage. *IEEE Communications Letters 20*, 8 (2016), 1647–1650.

[71] Mozaffari, M., Saad, W., Bennis, M., and Debbah, M. Unmanned aerial vehicle with underlaid device-to-device communications: Performance and tradeoffs. *IEEE Transactions on Wireless Communications 15*, 6 (2016), 3949–3963.

[72] Mozaffari, M., Saad, W., Bennis, M., Nam, Y. ., and Debbah, M. A tutorial on uavs for wireless networks: Applications, challenges, and open problems. *IEEE Communications Surveys and Tutorials 21*, 3 (2019), 2334–2360.

[73] Mucalo, A. K., Simac, G., and Tekovic, A. Criteria for mobile coverage obligations — overview in europe. In *2015 57th International Symposium ELMAR (ELMAR)* (Sep. 2015), pp. 181–184.

[74] Muruganathan, S. D., Lin, X., Maattanen, H.-L., Sedin, J., Zou, Z., Hapsari, W. A., and Yasukawa, S. An overview of 3gpp release-15 study on enhanced lte support for connected drones, 2019.

[75] NADDAFZADEH-SHIRAZI, G., LAMPE, L., VOS, G., AND BENNETT, S. Coverage enhancement techniques for machine-to-machine communications over lte. *IEEE Communications Magazine 53*, 7 (2015), 192–200. Cited By :15.

[76] NATIONS, U. Goal 9: Build resilient infrastructure, promote sustainable industrialization and foster innovation. www.un.org/sustainabledevelopment/infrastructure-industrialization/, 2019.

[77] NGUYEN, H. C., AMORIM, R., WIGARD, J., KOVACS, I. Z., SORENSEN, T. B., AND MOGENSEN, P. E. How to ensure reliable connectivity for aerial vehicles over cellular networks. *IEEE Access 6* (2018), 12304–12317.

[78] NGUYEN, H. C., AMORIM, R., WIGARD, J., KOVÁCS, I. Z., AND MOGENSEN, P. Using lte networks for uav command and control link: A rural-area coverage analysis. In *IEEE Vehicular Technology Conference* (2018), vol. 2017-September, pp. 1–6.

[79] NIESSEN, C. W. Battlefield connectivity via airborne communications nodes. In *Proceedings of SPIE - The International Society for Optical Engineering* (1997), vol. 3080, pp. 72–78.

[80] OFFICE OF COMMUNICATIONS OF UNITED KINGDOM. Connected nations report 2016. Tech. rep., OfCom, 2016.

[81] PALAZZI, C. E., ROSETI, C., LUGLIO, M., GERLA, M., SANADIDI, M. Y., AND STEPANEK, J. Satellite coverage in urban areas using unmanned airborne vehicles (uavs). In *2004 IEEE 59th Vehicular Technology Conference. VTC 2004-Spring (IEEE Cat. No.04CH37514)* (2004), vol. 5, pp. 2886–2890 Vol.5.

[82] PALAZZI, C. E., ROSETI, C., LUGLIO, M., GERLA, M., SANADIDI, M. Y., AND STEPANEK, J. Enhancing transport layer capability in haps-satellite integrated architecture. *Wireless Personal Communications 32*, 3-4 (2005), 339–356.

[83] PALIWAL, K. K., SINGH, S., AND BAJAJ, S. Rural communication enhancement using mobile ad-hoc network. In *2017 7th International Conference on Cloud Computing, Data Science Engineering - Confluence* (Jan 2017), pp. 387–391.

[84] PRIEGER, J. E. The broadband digital divide and the economic benefits of mobile broadband for rural areas. *Telecommunications Policy 37* (2013), 483–502.

[85] RENDON SCHNEIR, J., AND XIONG, Y. A cost study of fixed broadband access networks for rural areas. *Telecommunications Policy 40*, 8 (2016), 755–773. Technological change and the provision, consumption and regulation of services: Papers from a European ITS regional conference.

[86] RUDD, R. F. Indoor coverage considerations for high-elevation angle systems. In *Second International Conference on 3G Mobile Communication Technologies* (March 2001), pp. 171–174.

[87] SAAD, W., HAN, Z., BAŞAR, T., DEBBAH, M., AND HJØRUNGNES, A. A selfish approach to coalition formation among unmanned air vehicles in wireless networks. In *Proceedings of the 2009 International Conference on Game Theory for Networks, GameNets '09* (2009), pp. 259–267.

[88] SAHINGOZ, O. K. Mobile networking with uavs: Opportunities and challenges. In *2013 International Conference on Unmanned Aircraft Systems, ICUAS 2013 - Conference Proceedings* (2013), pp. 933–941.

[89] SAHINGOZ, O. K. Networking models in flying ad-hoc networks (fanets): Concepts and challenges. *Journal of Intelligent and Robotic Systems: Theory and Applications 74*, 1-2 (2014), 513–527.

[90] SAUNDERS, S., AND ARAGÓN-ZAVALA, A. *Antennas and Propagation for Wireless Communication Systems*. Wiley, 2007.

[91] SECRETARY-GENERAL. Progress towards the sustainable development goals. Tech. rep., United Nations, 2020.

[92] SETIAWAN, E. The potential use of high altitude platform station in rural telecommunication infrastructure. In *2018 International Conference on ICT for Rural Development (IC-ICTRuDev)* (2018).

[93] SHAKHATREH, H., SAWALMEH, A. H., AL-FUQAHA, A., DOU, Z., ALMAITA, E., KHALIL, I., OTHMAN, N. S., KHREISHAH, A., AND GUIZANI, M. Unmanned aerial vehicles (uavs): A survey on civil applications and key research challenges. *IEEE Access 7* (2019), 48572–48634.

[94] SHARMA, V., BENNIS, M., AND KUMAR, R. Uav-assisted heterogeneous networks for capacity enhancement. *IEEE Communications Letters 20*, 6 (2016), 1207–1210.

[95] SHARMA, V., SRINIVASAN, K., CHAO, H. ., HUA, K. ., AND CHENG, W. . Intelligent deployment of uavs in 5g heterogeneous communication environment for improved coverage. *Journal of Network and Computer Applications 85* (2017), 94–105.

[96] SMIRNOV, N. I., EREMICHEV, V. I., AND TSYRENOVA, L. A. Increase in the efficiency of the coverage area in the cellular communication systems. In *2017 Systems of Signal Synchronization, Generating and Processing in Telecommunications (SINKHROINFO)* (July 2017), pp. 1–4.

[97] SOOEUN SONG, MINSU CHOI, Y. G. J. Y. W. Y. W. Y. J. J. J.-M. C. . Analysis of wireless backhaul networks based on aerial platform technology for 6g systems. *Computers, Materials & Continua 62* (2020).

[98] SUNDQUIST, M., AND MARKENDAHL, J. A case study cost modelling of regulatory alternatives to mitigate the mobile network coverage and capacity problems in rural areas. 26th European Regional Conference of the International Telecommunications Society (ITS): "What Next for European Telecommunications?", Madrid, Spain, 24th-27th June, 2015, International Telecommunications Society (ITS).

[99] TANG, Y. F., ZHANG, Y. X., AND KAN, S. L. Indoor rf signal coverage solution. In *2017 IEEE Asia Pacific Microwave Conference (APMC)* (Nov 2017), pp. 233–236.

[100] VATALARO, F., CORAZZA, G. E., CAINI, C., AND FERRARELLI, C. Analysis of leo, meo, and geo global mobile satellite systems in the presence of interference and fading. *IEEE Journal on selected areas in communications 13*, 2 (1995), 291–300.

[101] VILLAPOL, M. E., LIU, W., GUTIERREZ, J., QADIR, J., GORDON, S., TAN, J., CHIARAVIGLIO, L., WU, J., AND ZHANG, W. A sustainable connectivity model of the internet access technologies in rural and low-income areas. In *Smart Grid and Innovative Frontiers in Telecommunications* (Cham, 2018), P. H. J. Chong, B.-C. Seet, M. Chai, and S. U. Rehman, Eds., Springer International Publishing, pp. 93–102.

[102] WANG, H., DING, G., GAO, F., CHEN, J., WANG, J., AND WANG, L. Power control in uav-supported ultra dense networks: Communications, caching, and energy transfer. *IEEE Communications Magazine 56*, 6 (2018), 28–34.

[103] WANG, J., JIANG, C., HAN, Z., REN, Y., MAUNDER, R. G., AND HANZO, L. Taking drones to the next level: Cooperative distributed unmanned-aerial-vehicular networks for small and mini drones. *IEEE Vehicular Technology Magazine 12*, 3 (2017), 73–82.

[104] WANG, K., ZHANG, R., WU, L., ZHONG, Z., HE, L., LIU, J., AND PANG, X. Path loss measurement and modeling for low-altitude uav access channels. In *IEEE Vehicular Technology Conference* (2018), vol. 2017-September.

[105] YAEL MAGUIRE. High altitude connectivity: The next chapter. https://engineering.fb.com/2018/06/27/connectivity/high-altitude-connectivity-the-next-chapter/, 2018.

[106] YANMAZ, E. Connectivity versus area coverage in unmanned aerial vehicle networks. In *IEEE International Conference on Communications* (2012), pp. 719–723.

[107] YAZDANI, O., AND MIRJALILI, G. A survey of distributed resource allocation for device-to-device communication in cellular networks. In *19th CSI International Symposium on Artificial Intelligence and Signal Processing, AISP 2017* (2018), vol. 2018-January, pp. 236–239. Cited By :1.

[108] YILMAZ, O. N. C., TEYEB, O., AND ORSINO, A. Overview of lte-nr dual connectivity. *IEEE Communications Magazine 57*, 6 (2019), 138–144.

[109] ZENG, Y., ZHANG, R., AND LIM, T. J. Wireless communications with unmanned aerial vehicles: Opportunities and challenges. *IEEE Communications Magazine 54*, 5 (2016), 36–42.

[110] ZHANG, S., ZENG, Y., AND ZHANG, R. Cellular-enabled uav communication: A connectivity-constrained trajectory optimization perspective. *IEEE Transactions on Communications 67*, 3 (2019), 2580–2604.

[111] ÖZGÜR ERÇETIN, KRISHNAMURTHY, S., DAO, S., AND TASSIULAS, L. Provision of guaranteed services in broadband leo satellite networks. *Computer Networks* (2002).