Ph.D. Project:

Optimal design of 5G wireless networks with UAV-based Free-Space Optical Backbone in rural and low-income regions for a DEMOcratic access to internet CONnectivity (DEMOCON)

Location:

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Context of the Ph.D. Project

In the last two decades, wireless telecommunications have known an incredible evolution and spread and now constitute a fundamental part of our everyday life. Thanks to them, it is possible to get an ubiquitous and very fast access to the internet and to a wide range of telecommunication services, which can make our everyday life easier.

However, such technological conquest presents a dark side: the cited developments have almost exclusively interested the most densely inhabited regions of western countries. In these regions, the deployment of high-performance but costly networks is justified by the high revenue from people who are disposed to pay more for better and faster telecommunications services. In contrast, rural and low-income zones have been highly ignored by wireless network operators, when deploying high-performance networks: they are not attractive from an economical point of view, since they either present a too low population and thus too few potential customers or a population that cannot afford the advanced connectivity services. Such zones are thus highly disadvantaged and present a serious technological gap with respect to urban and richer zones.

Nowadays, there are still two billions of people in the world that completely lack wireless service coverage [ErVB15] and this cuts them off from communicating with the rest world. This lack is a very serious issue, since telecommunications services such as internet are now considered an essential commodity like water, food and energy, which can deeply affect the economical and social evolution of a country, as discussed in [UniSo16]. Additionally, this lack prevents the access to essential e-learning and e-healthcare services, which can greatly contribute to increase the conditions of life in the poorest area of the planet and reduce the gap with respect to more advanced countries.

In this context, the next generation of wireless networks (5th Generation, or briefly 5G - see e.g., [5G-WP]) represents a new very promising technology for a democratic access to internet connectivity and telecommunications services in rural and low-income regions. According to the vision expressed in [ChEtAl16] by prominent telecommunication researchers, the reusability of network components and functions, which is a key feature of 5G, will allow the deployment of low-cost network infrastructure that can implement intelligent and flexible allocation of network resources, bringing connectivity and computing capacity where it is really needed. Such flexible and dynamic allocation will provide also an effective way to deal with user position and traffic uncertainty, allowing to follow the customers and provide more or less capacity depending on the traffic demand of users.

In "traditional" wireless network up to 4th Generation (here denoted as PRE-5G), each network node had to install all the hardware and software needed to provide a specific network function. In contrast, 5G networks support what has been called "superfluidity": network functions can be decomposed into elementary reusable components called *Reusable Functional Block* (RFB), which must not necessarily be installed in the node providing the function, but can distributed into multiple different nodes and can serve other multiple RFBs located in other nodes. Such RFBs can be dynamically moved where they are needed depending upon traffic demand. Additionally, "chains" of RFBs located in distinct nodes can be combined to define more complex functions and thus refined telecommunications services.

The magic of using RFBs is that costly and complex pre-5G base stations can be replaced by a coordinated network of low-cost and low-complexity communicating devices. As prospected in [ChEtAl16] in the case of rural and low-income regions, these devices would be represented mainly by: 1) very-large-coverage low-complexity base stations, providing service connectivity up to 50 km; 2) small solar-powered wireless nodes, providing coverage over small areas; 3) Unmanned Aerial Vehichles (UAVs), moving around medium-sized areas and providing dynamic coverage; 4) portable personal communication devices like smartphones.

Moreover, in order to keep greatly contained the complexity and cost of the backbone network, backbone communications are based on Free Space Optical (FSO) communications technology ensured by FSO devices mounted on an ad-hoc fleet of UAVs. These UAVs thus actually represent nodes of a “flying” backbone, whose cost is dramatically lower with respect to traditional optical-fiber-based backbones, which typically require very high digging costs that are justified only in dense modern metropolis characterized by high incomes [YaAl20].

This constitutes a network of communicating devices**,** whose deployment introduces new much more complicated optimal network design problems that in the past. Indeed, the design of traditional pre-5G networks essentially consisted of deciding where to deploy and how to configure the base stations in order to provide service coverage to a target area (see e.g., [DAMaSa13]). In contrast, in the 5G networks that we prospect, we must decide not only how to deploy and configure the base stations, but also decide:

1. where to deploy and how to configure the small wireless nodes;
2. where to deploy and how to move UAVs around a target area;
3. where to deploy and how to move UAVs with FSO devices constituting the backbone network;
4. how to include personal communications devices, such as smartphones, as potential additional nodes of the network;
5. how to allocate the *Reusable Functional Blocks* (RFBs) to the base stations, nodes and UAVs, so to cover a rural or low-income target region, while taking into account the uncertainty of traffic generation (localization of users and volume of traffic generated) and minimizing the total cost of deployment.

To the best of our knowledge, such integrated wireless network design problem based on Free Space Optical communications involving so different communicating devices has received very little attention and there is a lack of optimization models and algorithms for it. The topic of traffic uncertainty has also been neglected in 5G network design operated by optimization techniques.

However, when investigating the problem we will profit from the recent literature that has dealt with the design of urban high-performance superfluid 5G networks (e.g., [BiEtAl16, BiEtAl17]) and the use of UAVs for providing wireless coverage (e.g., [MoEtAl16]).

Expected Main Phases of the Ph.D. Project

The Ph.D. project is going to be articulated in the following 4 main phases.

Phase 1 – Literature study and identification of the 5G optimal network design problem. After an exhaustive review of the state-of-the-art concerning the addressed topics, this phase will be aimed to reach a clear description of the 5G optimal network design problem that will be addressed. A critical task will be also to identify how to take into account the uncertainty of traffic generation of users, which critically affects the need for network capacity.

Phase 2 - Modelling the 5G design by a Robust Optimization model and polyhedral study. The first objective of the WP will be to define a reference *deterministic* version of the design problem, namely a version of the problem not considering data uncertainty. We expect to derive a reference Integer Linear Programming optimization problem, including binary variables to represent decisions like: 1) the deployment of network devices (e.g., base stations, nodes and UAVs); 2) the assignment of devices providing telecommunications service to users; 3) the allocation of RFBs to the communications devices; 3) the positioning of the UAVs with FSO devices constituting the backbone network; 3) the path adopted by UAVs to provide service coverage in the target area.

The second objective of the WP will be to derive a *robust counterpart* of the problem, namely a modified version of the deterministic problem that takes into account the presence of data uncertainty. The methodology that we expect to adopt to tackle data uncertainty is Robust Optimization (RO) [BeBrCa11, BuDA12]), which takes into account data uncertainty under the form of hard constraints that cut off all solutions not protected against deviations in the input data of the problem. It is also expected to make a *polyhedral study* of the mathematical formulation of the problem, in order to derive *robust valid inequalities* that can improve the mathematical strength of the formulation. In particular, we plan to derive robust version of valid inequalities that express conflicts of existence between communicating devices, similarly to [DAMaSa13].

Phase 3 - Developing optimization algorithms for the solution of the problem. As indicated by several recent studies (e.g, [ChEtAl19, ChEtAl20] and the references therein), solving optimization problems related to the design of 5G networks employing UAVs is a very challenging task: even state-of-the-art optimization solvers may find extremely difficult to solve the problem. As a consequence, we realistically expect that we will not be able to solve the developed models by a straightforward application of a software and the definition of ad-hoc exact and heuristic solution algorithms will represent a crucial part of the Ph.D. investigations.

Phase 4 - Definition of realistic problem instances and computational tests. We plan to collect realistic and real-world data from professionals and researchers who are interested in the 5G network design problem, in order to define relevant optimization models for the problem and have a realistic assessment of the performance of the new proposed approaches. These data will be used to derive meaningful instances for the studied robust optimization problems.

We plan to put the problem instances generated in this WP at disposal of the scientific community on the website of the Université de Technologie de Compiègne. These data will be very useful for the entire community as a standardized benchmark for evaluating and comparing models and algorithms for (robust) 5G networks.

Expected impact of the investigations

The new developed Robust Optimization models and algorithms will prove useful not only for advancing the theory of Robust Optimization for network design, but will also fill a scientific gap about models and algorithms for the design and management of 5G networks. Moreover, thanks to the cooperation with experts of 5G, we will develop models and algorithms that will be practically relevant and possibly transferable to telecommunications companies for supporting their network design decision process.

The models, algorithms and computational studies of the project will prove useful to support the cost-efficient deployment of cheap wireless technological solutions to provide internet connectivity in rural zone of Metropolitan France and low-income zones of "*France d'outre-mer*", contributing to reduce their "digital-divide" with respect to more densely and richer inhabited parts of Metropolitan France.

Furthermore, the results of the study on the integration of base stations and UAVs to form a low-complexity network could be adapted to the problem of providing wireless service coverage in emergency situations, such as natural disasters, when a territory can become isolated due to damages to the wired and wireless telecommunications infrastructures.

Candidate's profile:

Applicants must have a Master Degree (or equivalent) in Computer Science, Applied Mathematics, Industrial Engineering or any related discipline. Applicants should demonstrate proficiency in English, good programming skills and knowledge of mathematical optimization. Experience on the development of models and algorithms for telecommunication system design will be appreciated.

Documents required to apply:

Please send to d.andreagiovanni@hds.utc.fr, hicham.lakhlef@hds.utc.fr and madjid.bouabdallah@hds.utc.fr

- a curriculum vitae
- a motivation letter
- at least two references and/or recommendation letters
- a statement of research interests and experience (if any)

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