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Addressing Cooperation between Mobile Operators in Telecommunication Networks via Optimization: A Lexicographic Approach and Case Study in Colombia

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Abstract

Cooperation between Telecommunications (Telco) operators has been limited both by regulation and competition in previous years. However, cooperation could not only allow an overall growth in quality of service (QoS) but also may benefit companies with under exploited nodes in their network infrastructure. This way, both fully deployed infrastructure by single Telco companies, as well as smaller companies with increasing service demand but low infrastructure deployment could potentially benefit from cooperation agreements. This article proposes a lexicographic mixed-integer linear optimization model for Telco cooperation composed by two phases: Phase 1 maximizes the number of services connected to the current infrastructure assuming cooperation between operators while Phase 2 minimizes the costs of connecting such services. We built a simple base scenario that allowed us to validate the intuition behind our model. Furthermore, to demonstrate the applicability of our lexicographic optimization model for cooperation between mobile operators, we present a real-world case study in a rural area in Colombia that allowed us to find the marginal costs of additional national roaming connections, as well as marginal profits under the cooperation schema. Our results could help mobile operators to benefit from cooperation and, since the model adapts to the local necessities of the company, cooperation could be restricted to any desired level.

Keywords: Cooperation, telecommunications, heterogeneous network, mixed-integer linear programming, lexicographic.

1 Introduction

As technology in mobile telecommunications continues to improve, demand grows to a point where connected devices outnumber the population [12]. IoT and 5G technology bring new challenges to existing and future infrastructure as the number of connected devices will grow exponentially. Cooperation between existing telecommunication operators (Telco operators) will not only give them a competitive advantage against new entrants, but it will position them strategically for this technology revolution [3]. By cooperating, operators could increase their service level, make a profit, and provide the best quality of service (QoS) leveraging on other Telcos when the deployment of new infrastructure gets expensive. Areas of low-density populations will start to gain more and more demand with IoT and autonomous vehicles, but even today as services demand more resources with more latency requirements this topic becomes relevant.

An example of cooperation occurs in Colombia (South America), where the regulation requires mobile operators to cooperate if requested by another operator [12], both to improve QoS provided and to allow easy customer growth while deploying new infrastructure. However, initially, this regulation included only the country's large mobile operators who had the deployed infrastructure necessary to provide service in most of the territory: Movistar, Claro, and Tigo. This regulation also imposes constraints on the cooperation costs and guides virtual mobile operators (VMOs) to improve their competitiveness in the market by making different agreements with telecommunications operators (Telcos) with deployed infrastructure [3]. It also enables new incoming operators to offer services, not only in large cities (where they do start to deploy their infrastructure) but in rural areas where infrastructure for new competitors could take a lot of time to settle: e.g., Avantel in the Colombian case. This regulation takes a role in decreasing possible monopolies and increasing the offer of mobile services to the entire population. Moreover, as Telcos coverage varies a lot because of the geography, without a cooperated-planned deployment of infrastructure, the only other way to minimize cost providing high QoS is establishing agreements for cooperating with the current infrastructure. With cooperating parameters, personalization, and granular decision making, all the Telcos that could participate in the cooperation could benefit in one way or another. Despite all the benefits cooperation could bring, tools that enable Telcos to determine specific guidelines to cooperate are still an open discussion topic.

In this paper, we propose a 2-phase lexicographic optimization model that enables Telcos to connect the maximum number of devices requesting services at a minimum cost under a cooperation scheme. The model acts as an intermediate that orchestrates operators so that the connections can be accomplished with all fairness. To demonstrate the applicability of our model, we use two test instances. The first instance, a simple scenario, serves to demonstrate the correctness of the model. The second instance, a real-world scenario from the Colombian case, serves to measure the scalability of the model. Our results indicate that we could effectively implement the model with different cooperation strategies that would benefit mobile operators and their users. With this approach, the viability of cooperation increases exponentially as ultra-personalization comes in the picture.

This paper is organized as follows. Section 2 presents a literature review on whatever comes here. Section 3 presents the formulation of our lexicographic model. Section 4 presents the computational experiments in the two test instances. Finally, Section 5 concludes the paper and outlines current and future work.

2 Literature review

Heterogeneous networks have been a trending topic recently. Its close relationship with innovation and its association with a contribution to country development has generated great interest among various research areas, inspiring different investigations with a wide arrange of scopes. Many of these investigations focus on topics such as optimization, load balancing, quality of services, among others [7, 10, 13, 15, 23].

Optimizing the resources with which a service is offered is a highly relevant issue, given the high demand volume today. For example, in Colombia, where more than 65 million mobile lines [12] translates into 1.97 mobile lines per user [5], demand for mobile data has been increasing exponentially over the past decade, and users demand lower rates per GB consumed every year. Thence, there are many opportunities within the optimization approach, depending on the scope used in the research. For example, Feng [9] used an algorithm to optimize the number of sub-channels used in the spectrum to increase the system capacity. Demirtas [6] tried to optimize the efficiency in the energy used by the micro and macro cells of a heterogeneous cellular network. Now, there is plenty of information about Telco optimization and all the different scopes that these approaches can have, however, an even more striking issue is a cooperation between mobile operators as a strategy to improve their operating conditions. Oikonomakou [17] shows how cooperation between mobile operators helps improve energy consumption in times of low demand, improving the costs of the operators involved. Also, Poyhonen [16] demonstrates that in a network where operators cooperate, the total use of the network is much higher and therefore represents benefits both for operators and end-users since service quantity and quality is increased. Thus, in this paper we propose an optimization model that considers the resources being demanded by the users and determines how Telcos should provide them under a cooperation scheme.

On the other hand, most of the literature about heterogeneous networks focus on urban areas, where there is a high concentration of users and high demand for services. However, over the past decade there has been a big effort being made to try and reach the remote areas in different countries around the world. Nevertheless, to the best of our knowledge, research about heterogeneous networks in rural areas is scarce. One of the few works in this domain is presented by Ting [22], that seeks to provide the greatest possible coverage to satisfy the requirements of users while minimizing the number of resources required without sacrificing the QoS.

In this paper, we propose a lexicographic optimization model Telcos cooperation in rural areas to improve the QoS on areas with low antenna density and, typically, low user concentration, but with potential exponentially user growth. We also analyze this model from an economic perspective to study its viability and possible profitability. Finally, we present a case study in one of Colombia's main roads, where users flow multiply significantly at specific times of the year, and then, reduce drastically.

3 Mathematical model

Our optimization model is a lexicographic mixed-integer linear programming (MILP) model which proposes a cooperation alternative between current mobile operators in the telecommunications sector. Our goal is to provide users the best possible service, considering the cost of such cooperation. Figure 1 presents the general outline of our lexicographic model, which comprises two phases. In the first phase, we maximize the quality of service provided by maximizing the number of connected services from those demanded. To do so, we allow cooperation between the operators. Thus, any device can be connected to any antenna, even when they do not have an established contractual relationship with the operator of that antenna. The second phase minimizes the cost of the connections established in the first phase under the cooperation scheme.

3.1 Phase 1

The first phase of our lexicographic model finds the maximum number of services that can be satisfied with the available infrastructure of all mobile operators. Let $\mathcal{O}$ be the set of operators that will cooperate. Let $\mathcal{D}$ be the set that contains all users' devices. Let $\mathcal{S}$ be the set of services that a device can demand. These services have different consumption requirements, as well as different latency requirements to achieve what will be defined from now on as a "good QoS". Finally, let $\mathcal{A}$ be the set of antennas to which a user can connect to.

Alongside the sets presented above, it is necessary to define the following binary parameters to understand and establish all the relationships in the model. First, binary parameter α_{ao} takes the value of one if antenna $a \in \mathcal{A}$ belongs to operator $o \in \mathcal{O}$; it takes the value of zero otherwise. From this parameter, we create a subset $\mathcal{A}_o = \bigcup_{a \in \mathcal{A} | \alpha_{ao}=1} \{a\}$, which groups the devices of users with a contractual relationship to operator $o \in \mathcal{O}$. Binary parameter δ_{do} takes the value of one if the user who owns device $d \in \mathcal{D}$ has a contractual relationship with operator $o \in \mathcal{O}$.

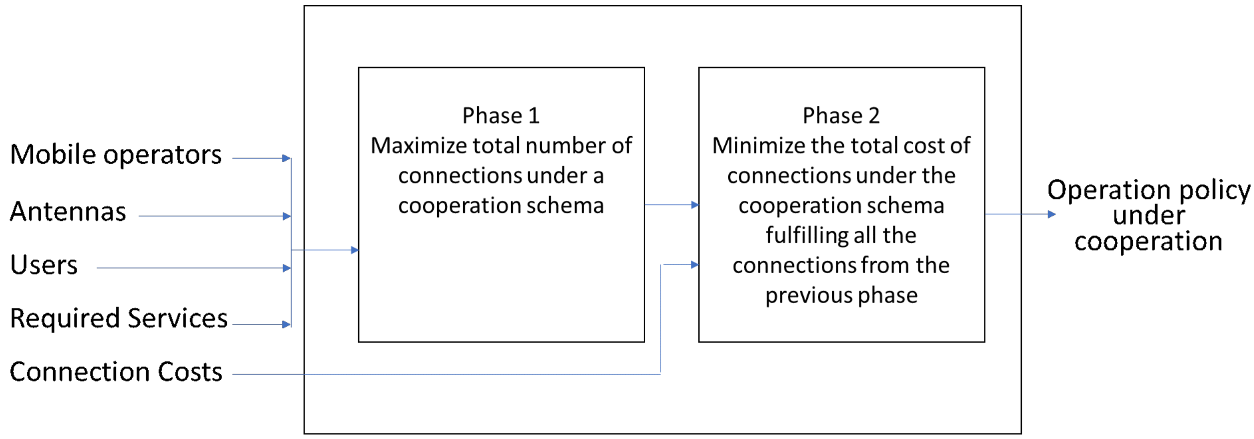

Figure 1: General outline of the cooperation model between telecommunications operators

Finally, it is important to understand that at any given time, a device may be using multiple services simultaneously. Binary parameter β_{ds} takes the value of one if device $d \in \mathcal{D}$ is using service $s \in \mathcal{S}$; it takes the value of zero otherwise. From this parameter, we create a subset $\mathcal{S}_d = \bigcup_{s \in \mathcal{S} | \beta_{ds}=1} \{s\}$ which groups the services being used in device $d \in \mathcal{D}$.

The antennas have a peak of upload and download speed according to their infrastructure, this means that this speed must be divided among the users connected to this base, which can affect their QoS [14]. Depending on various other factors such as the operator owner or the geographical position, every single antenna will have different average bandwidth available. Thus, we have defined a total bandwidth capacity c_a on every antenna $a \in \mathcal{A}$. Likewise, based on the studies presented by Huidobro [14] that states that antennas cannot support infinite connections and have a maximum of connections over a specific range, we established a limit l_a of possible connections to an antenna $a \in \mathcal{A}$.

The connection range varies among antennas as well depending on the radios installed. Thus, for a device to connect to an antenna $a \in \mathcal{A}$, it must be within a maximum distance z_a. Users above this distance will not receive enough signal strength to satisfy their demand for services with a good QoS.

To make a fair approach to the reality of cooperation, we also defined a percentage p_a of the bandwidth of antenna $a \in \mathcal{A}_o$ destined to be shared with users with no contractual relationship with operator $o \in \mathcal{O}$. Thus, we allowed a different percentage of cooperation on every single antenna to limit the amount of bandwidth to share. This allows operators to avoid the antennas' saturation in places where there is a high demand of services, which will result in prioritizing the users of the company that owns the antenna.

To determine if a connection can be established between device $d \in \mathcal{D}$ and antenna $a \in \mathcal{A}$ to satisfy any of the services $\mathcal{S}_d$, we use theoretical formulas of received signal strength (RSS) that relate to the distance n_{da} between the device and the antenna [8]. In addition to the RSS, to determine if a connection between a device and an antenna can be established to satisfy a specific service $s \in \mathcal{S}$, we also check the requirement of bandwidth r_s necessary to satisfy the service with such connection. Thus, to provide good QoS on a service $s \in \mathcal{S}$ with a connection to an antenna, the device demanding the service must be within a fraction q_s of the range of the connected antenna. This allows us to ensure the latency requirements for each service.

Our lexicographic model considers a binary decision variable x_{das}, which takes the value of one if there is a connection between a device $d \in \mathcal{D}$ and an antenna $a \in \mathcal{A}$ to satisfy service $s \in \mathcal{S}$ required, which allows identifying all the connections established in the model. We summarize the previous notation in Table 1.

Table 1: Notation table for the lexicographic model

Lexicographic model	
Sets	
$\mathcal{O}$	Set of mobile operators that will cooperate.
$\mathcal{A}$	Set of antennas of the mobile operators.
$\mathcal{D}$	Set of users' devices.
$\mathcal{S}$	Set of services.
Binary parameters to build subsets	
α_{ao}	1 if $a \in \mathcal{A}$ belongs to operator$o \in \mathcal{O}$, 0 otherwise.
δ_{do}	1 if user of device $d \in \mathcal{D}$ has a contract with operator $o \in \mathcal{O}$, 0 otherwise.
β_{ds}	1 if service $s \in \mathcal{S}$ is being used in device $d \in \mathcal{D}$.
Subsets	
$\mathcal{A}_o$	Subset of antennas of operator $o \in \mathcal{O}$.
$\mathcal{D}_o$	Subset of devices whose user have a contract with operator $o \in \mathcal{O}$.
$\mathcal{S}_d$	Subset of services being used in device $d \in \mathcal{D}$.
Labels	
$f(d)$	Operator with whom user of device $d \in \mathcal{D}$ has contract.
Parameters of the Phase 1 of the lexicographic model	
u_a	Upper bound for the bandwidth capacity of antenna $a \in \mathcal{A}$.
k_a	Maximum number of connections allowed to antenna $a \in \mathcal{A}$.
z_a	Maximum distance for a device to antenna $a \in \mathcal{A}$.
p_a	Maximum percentage of the bandwidth of antenna $a \in \mathcal{A}_o$ available to provide services of devices whose user have no contract with operator $o \in \mathcal{O}$.
r_s	Required bandwidth to satisfy service $s \in \mathcal{S}$.
q_s	Maximum fraction within an antenna's range to provide service $s \in \mathcal{S}$.
n_{da}	Distance between device $d \in \mathcal{D}$ and antenna $a \in \mathcal{A}$.
Parameters of the Phase 2 of the lexicographic model	
W^*	Optimal value of the objective function (1).
c_{ao}	Unitary (Mbps) cost of connection from the devices of every operator $o \in \mathcal{O}$ to every antenna $a \in \mathcal{A}$.
Decision variables	
x_{das}	1 if device $d \in \mathcal{D}$ connects to antenna $a \in \mathcal{A}$ to satisfy service $s \in \mathcal{S}_d$.

The mathematical formulation of the first phase of our lexicographic model is shown in equations (1)-(7).

$$\text{maximize} \quad W = \sum_{d\in\mathcal{D}} \sum_{a\in\mathcal{A}} \sum_{s\in\mathcal{S}_d} x_{das} \tag{1}$$

Subject to,

$$\sum_{a\in\mathcal{A}} x_{das} \leq 1, \qquad \forall\ d \in \mathcal{D}, s \in \mathcal{S}_d; \tag{2}$$

$$\sum_{d\in\mathcal{D}} \sum_{s\in\mathcal{S}_d} x_{das} \leq k_a, \qquad \forall\ a \in \mathcal{A}; \tag{3}$$

$$\sum_{d\in\mathcal{D}} \sum_{s\in\mathcal{S}_d} r_s x_{das} \leq u_a, \qquad \forall\ a \in \mathcal{A}; \tag{4}$$

$$\sum_{d\in\mathcal{D}|d\notin\mathcal{D}_o} \sum_{s\in\mathcal{S}_d} r_s x_{das} \leq p_{ao} u_a, \qquad \forall\ o \in \mathcal{O}, a \in \mathcal{A}_o; \tag{5}$$

$$x_{das} \leq q_s \frac{z_a}{n_{ad}}, \qquad \forall\ d \in \mathcal{D}, a \in \mathcal{A}, s \in \mathcal{S}_d; \tag{6}$$

$$x_{das} \in \{0, 1\}, \qquad \forall\ d \in \mathcal{D}, a \in \mathcal{A}, s \in \mathcal{S}_d. \tag{7}$$

Objective function (1) maximizes the total amount of connections to antennas to provide the different services demanded by the devices. Constraints (2) prevent a service to be fulfilled or satisfied by more than one antenna. Constraints (3) limit the number of connections to each antenna. Constraints (4) guarantee the available bandwidth in every antenna is not exceeded by the services connected to it. Constraints (5) impose an upper bound to the available bandwidth for cooperation in the antennas of every operator. To do so, the left-hand side sums the bandwidth demanded by the services in other operators' devices and the right-hand side specify a maximum bandwidth for cooperation with other operators. Constraints (6) prohibit connections to antennas of devices outside the coverage zone of the antenna (i.e., $\frac{z_a}{n_{ad}}$). Furthermore, (6) also guarantee latency requirements to satisfy the demanded services (i.e., q_s). Finally, constraints (7) describe the variables' domain.

3.2 Phase 2

Optimization model (1)-(7) finds the maximum number of services that can be satisfied under the cooperation scheme. We retrieve the optimal value of objective function (1) and store it in parameter W^*. Phase 2 of our lexicographic model minimizes the total cost of those connections.

In many countries, regulations impose an upper monetary limit for the cooperation between Telcos operators; and guides virtual mobile operators (VMOs) to improve their competitiveness in the market by making different agreements with established Telcos with deployed infrastructure. [3] We acknowledge that establishing the same commercial relationship with all other operators is not a feasible solution for many different reasons. For such reason, we determined a fixed unitary (Mbps) cost of connection c_{ao} from the devices of every operator $o \in \mathcal{O}$ to every antenna $a \in \mathcal{A}$. These costs are low between devices and antennas of the same operator. Nevertheless, it can vary between antennas because of their geographic location and other external factors. This allows us to further increase the conditions of cooperation and possible new entrants.

The mathematical formulation of the seconds phase of our lexicographic approach is presented in equations (8) and (9).

$$\text{minimize} \quad \sum_{d\in\mathcal{D}} \sum_{a\in\mathcal{A}} \sum_{s\in\mathcal{S}_d} c_{a,f(d)} r_s x_{das} \tag{8}$$

Subject to,

$$(2) - (7)$$

$$\sum_{d\in\mathcal{D}} \sum_{a\in\mathcal{A}} \sum_{s\in\mathcal{S}_d} x_{das} \geq W^*. \tag{9}$$

Objective function (8) minimizes the total cost of connections. Recall that label $f(d) = o \in \mathcal{O}$ retrieves the operator with whom the user of device $d \in \mathcal{D}$ has contract. Thus, $c_{a,f(d)}$ quantifies the cost of transmitting 1 Mbps from antenna $a \in \mathcal{A}$ to device $d \in \mathcal{D}$ based on these contractual relationships. Constraints (2)-(7) guarantee the same operational conditions as Phase 1.

Finally, constraints (9) ensure the same number of satisfied services determined in Phase 1 of our lexicographic model. By ensuring all the above, it is possible to find the best possible service under a cooperative scenario, guaranteeing minimum-cost operation for Telcos operators.

4 Computational experiments

To demonstrate the applicability of our lexicographic model to cooperate between Telcos operators, we recreated two scenarios. The first one, the Base Scenario, is a small test instance that demonstrates the advantages of our model in terms of connected services and the cost of those connections under the cooperation scheme. The second scenario is a real-world rural scenario along a highway in Colombia; we selected this scenario because it is a low-density area, where demand varies a lot depending on weather, traffic, date of the year, among others. Also, it is the best scenario where the deployment of new infrastructure is significantly more expensive than in cities or dense areas.

4.1 Base scenario description

For the base scenario, we defined a study area of ten square kilometers of an open field. In this scenario, we established a highway defined by the line $y = x$, that traverses all the study area. Thus, the highway in the Base Scenario is 14.1421 km long.

We decided to have three mobile operators (i.e., $i = 1, 2, 3$), each one with three antennas each (i.e., $j = 1, 2, 3$), thus, we considered nine antennas in our Base Scenario. To locate every antenna $k = 1, \dots, 9$ along the highway in the Base Scenario, we randomly generated its horizontal and vertical position as follows: the horizontal position X_k of antenna $k = 1, \dots, 9$ follows a continuous uniform distribution between zero to ten (i.e., $X_k \sim U(0, 10)$); the vertical position Y_k of antenna $k = 1, \dots, 9$ follows a triangular distribution based on its horizontal position and maximum 300 meters away from the road (i.e., $Y_k \sim Triangular(X_k - 0.3, X_k, X_k + 0.3)$). We assigned the following parameters to each antenna: its identifier (from 1-9), its maximum number of connections, its bandwidth rate, its cooperation percentage, its theoretical range, and the maximum percentage of its bandwidth to share with other mobile operators.

To assign the bandwidth available, we used an instance of a variable following a discrete uniform distribution between 800 and 1000 MB/s. To assign the total number of possible simultaneous connections we used an instance of a random variable following a discrete uniform distribution between 20 and 50 connections. Later, we assigned the range of an antenna as an instance of a random variable following a discrete uniform distribution between one and three km; this was done because the equipped radios on the antennas are usually found in these ranges (i.e., 1000, 2000, or 3000), even though there are longer-range antennas, these ranges are the most used on highways based on statistics taken from [18]. The base configuration parameters for each antenna are presented in Table 2.

To establish the parameters to accomplish the cooperation, first, we defined the percentage of available bandwidth in each antenna by using an instance of a random variable following a continuous uniform distribution between 15% and 25%; and later we defined the costs as generic monetary units. We set up two connection costs to antennas: the first cost is related to the connections of users from the same company that owns the antenna, and the other one is related to the connection of users from another Telcos. For the first case, the cost determined was one generic monetary unit; and for the second, we assigned the cost as a uniform random variable with a distribution between 5 and 25 monetary units per MB consumed. The value of these parameters for the base case can be seen in Table 3.

We defined three types of possible services for this scenario: Service 0 is a high bandwidth-demanding service with low latency requirements, Service 1 is a medium bandwidth-demanding service with a medium latency requirement, and finally, Service 2 is a low bandwidth-demanding without strict

Table 2: Antennas configuration in the base scenario

Antenna	X Position	Y Position	Operator	Bandwidth	Connection Limit	Range
1	5.1	4.7225	0	864	23	2
2	0.2	0.5434	1	986	29	3
3	3.9	3.8243	2	896	36	1
4	2.4	2.6350	0	829	46	1
5	1.1	1.3085	1	819	41	1
6	6.5	6.3936	2	810	36	3
7	9.1	9.0472	0	865	40	3
8	4.2	4.2472	1	950	48	2
9	5.5	5.6837	2	853	42	2

Table 3: Antenna's cooperation percentage and costs of connection in the base scenario

Antenna	Cooperation %	Cost Operator 1	Cost Operator 2	Cost Operator 3
1	0.24	1.0000	6.9470	7.9863
2	0.19	7.0564	1.0000	10.283
3	0.24	6.9470	11.705	1.0000
4	0.18	1.0000	8.7521	6.4000
5	0.15	11.651	1.0000	8.9161
6	0.20	10.994	6.6188	1.0000
7	0.15	1.0000	6.9470	6.5094
8	0.18	7.2205	1.0000	10.228
9	0.22	8.4786	7.9863	1.0000

latency requirements. The value defined for the capacity and range requirements, of each service, can be seen in Table 4.

Table 4: Bandwidth requirements set for each service created in the base scenario

Service	Requirement MB/s	Percentage of Range
0	0.16	0.9
1	1.50	0.4
2	2.50	0.1

Finally, we generated 50 users distributed along the road. For this purpose, we used a random variable following a continuous uniform distribution between 0 and 10, to reduce the possibility of bias in to select the users' location near of the existing antennas (i.e. K U(0,10)). Also, to each user, we assigned a unique identifier and randomly defined both the mobile operator and the services used by this device. An example of the basic user's configuration generated can be seen in Table 5.

4.2 Base scenario results

Table 6 presents the results of our Case Study considering cooperation and no cooperation between the three operators in our Base Scenario. Among the three operators' users, there were 79 services being demanded. Without cooperation, only 22 of those connections were satisfied, but thanks to our lexicographic model for cooperation, this number raises to 52 under a cooperation scenario, achieving an increase on the overall service level of 136.33% (i.e., (65.82%-27.85%)/(27.85%)). However, there is a tradeoff in the cost of performing such operations. Without cooperation, the overall cost of the connections is \$10.22. Nevertheless, when cooperating, those 79 services can be connected at a

Table 5: Users' configuration in the base scenario

User	X position	Y position	Service 1	Service 2	Service 3	Operator 1	Operator 2	Operator 3
0	1.056	1.056	0	1	1	1	0	0
1	8.901	8.901	1	1	0	0	0	1
2	1.41	1.41	1	1	1	1	0	0
3	8.667	8.667	1	0	0	1	0	0
4	3.225	3.225	0	1	1	0	1	0

minimum cost of $311.23, representing a cost of a cooperative policy 3,222.89% higher (i.e., (311.23-10.22)/10.22).

Table 6: 2-Phase Results on the base scenario with and without cooperation

	Without Cooperation		With Cooperation	
Phase	Phase 1	Phase 2	Phase 1	Phase 2
Assigned Connections	22	22	52	52
Possible Connections	79	79	79	79
Lost Connections	57	57	27	27
Service Level	27.85	27.85	65.82	65.82
Total Cost	10.22	10.22	339.6	311.23

Although it is clear that the overall cost grew, since the loss of one operator means an income increase by another operator, we conducted an analysis on the income and the net profit of performing such connections in the model. Table 7 presents the roaming income, cost, and profit of every operator in both phases of our lexicographic model for cooperation. As noted, the second phase of our model is effectively reducing the roaming costs for all operators; likewise, we can observe how income is also modified in almost every case.

Table 7: Income, cost, and profit of every operator in every phase of the lexicographic model in the base scenario

Phase	Phase 1			Phase 2		
Operator	1	2	3	1	2	3
Roaming Income	107.051	155.066	69.726	115.152	124.824	61.038
Roaming Cost	141.087	52.873	137.883	116.473	49.196	135.345
Roaming Profit	-34.037	102.194	-68.157	-1.321	75.628	-74.307

Table 8 presents the total number of connections required by the users with a contractual relationship with every operator, as well as the number of connections accomplished with and without cooperation. For the first operator, the number of connections increased from 6 to 16 services, which represents an increase in the service level of 166.67%; for the second operator, it changed from 7 to 12 connections, increasing service level in 71.43%; and finally, for the third operator, it changed from 9 to 24, increasing its service level in 166,67%.

Although the main objective of our optimization model aims to reduce cost while cooperating, it reasonably enables every operator's roaming that could yield into income. Thus, it possible to establish every operator's net profit as well. Moreover, from the two previous analyses we determined the marginal cost of every additional connection made for every operator. This marginal cost can also be seen as an estimate on every Telcos' cost due to a lost connection. Table 9 presents the cost and profit of an additional connection for every operator. As a result, the marginal cost would not be

Table 8: Number of connections supplied with and without cooperation in the base scenario

Operator	Total Connections Required	Connections accomplished without cooperating	Connections accomplished cooperating
1	27	6	16
2	16	7	12
3	36	9	24

entirely fair. Although operator two has the least growth in the level of service offered (i.e., 71.43%), it has the greatest monetary benefit thanks to its cooperation with other operators.

Table 9: Marginal cost and profit for an additional connection using roaming

Operator	Cost Additional Connection	Profit Additional Connection
1	11.647	-0.132
2	9.839	15.126
3	9.023	-4.954

Finally, by taking the profit for every additional connection as a real connection cost after adjusting for the possible income, we could estimate the percentual growth in cost from a model without cooperation to a model with cooperation. When assuming a local operation of 1 for all operators (as the designed model does), Operator 1 undergoes an 86.8% decrease in its operating costs for roaming users (i.e., (1-0.132)/1); Operator 2 experiences an absolute decrease in connection cost because it receives income for every roaming user; and operator 3 experience an increase of 395.4% in the cost of every roaming user (i.e., (1-4.954)/1). From this we can observe that even though all operators benefit from increasing its service level, operators 1 and 2 also benefit from a cost reduction or even profit for the additional connections.

4.3 Case study description

The base scenario presented in the previous subsections served to check the correctness of our lexicographic model by proving it actually produces a cooperation strategy for Telcos and minimizes the overall cost of such cooperation. Nevertheless, it was a small mock scenario. To demonstrate the applicability of our approach, we implemented our model in a real-world Case Study on the rural section of a major artery in Colombia's road network. From this analysis we aim to observe both current and possible behaviors when implementing our model to find all the advantages and disadvantages of performing this cooperation strategy.

We focused our Case Study on a rural area around a section of an artery in Colombia's road network between Bogotá, Colombia's capital city, and Girardot, a small town nearby commonly used as vacations center: Bogotá-Girardot artery. This artery's section has low antenna density but high demand of services because it has a large volume of traffic with significant peaks at certain dates of the year. This could be considered an extreme- or a worst-case scenario for mobile operators. In Colombia, regulation requires mobile operators to cooperate if requested by another operator, both to improve QoS and to allow easy customer growth while deploying new infrastructure as starting companies in the country. However, initially, this regulation included only the country's large mobile operators, who had the deployed infrastructure necessary to provide coverage in most of the territory: Claro, Movistar, and Tigo (Telcos with deployed infrastructure).

This regulation sets the upper monetary limits and guides VMOs to improve their competitiveness in the market by making different agreements with established Telcos with deployed infrastructure

[3]. Table 10 presents theses monetary limits in Colombia for a specific date: May 4, 2017. This regulation also helps new incoming operators, like Avantel, to be able to offer services not only in large cities where they do start to deploy their infrastructure but in rural areas where infrastructure form new entrants could take a lot of time to settle. This regulation takes a role in decreasing possible monopolies and increasing the offer of mobile services to the entire population.

Table 10: Regulatory prices in Colombia for cooperation between mobile operators

Date	May 4, 2017
Cost for new competitors (MByte)	6.40
Cost for established competitors (Mbyte)	11.87

We used OpenStreetMap's API [18] to extract all the nodes in Bogotá-Girardot artery and reconstruct the highway. This information also served us to locate all the users we will consider in our case study along the road. To locate the antennas owned by the Telcos with deployed infrastructure (i.e., Movistar, Claro, and Tigo), we used the OpenCellID (OCID) API [19] to find all the antennas that were close to the area in our case study. Furthermore, from OCID's API we determined the range of the antenna, the technology used by the antenna (GSM, GRPS, UMTS, LTE), and the operator to which it belongs. Figure 2 presents the section considered of Bogotá-Girardot artery and the location of every operator's antennas. Some parameters of our model were not provided by OCID's API; to determine the antennas' capacity, we assumed on average 40 to 50 simultaneous connections. To determine the antennas' we assumed values between 800 and 1000 Mbit/s. However further sensibility analysis can be made.

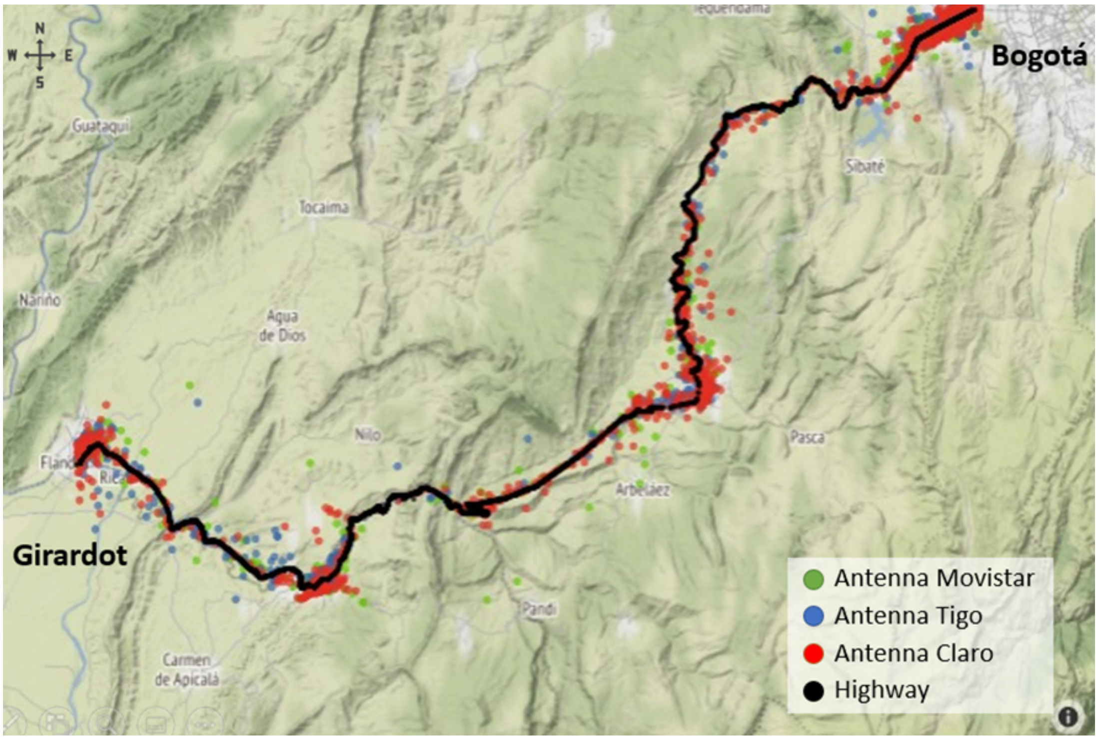

Figure 2: Bogotá-Girardot artery considered in the Case Study and operators' antennas

The services demanded by the users in our Case Study can be a VOIP call [4, 20], a song in Spotify [1, 21], and a short video on YouTube [2, 11]. We determined the download bandwidth required for each service and assumed the total amount of data they will consume to fully receive the entire service: complete a phone call for VOIP, listen to a full song for Spotify, and fully watch a video on YouTube. With this information we estimated the cost of each service while roaming based on the Colombian regulation, mentioned above, as a value between the minimum (i.e., $ 6.4) and the maximum cost (i.e., $ 11.87) [3]. Finally, we randomly allocated these services to each user, as well as the mobile operator a user had a contractual relationship with the same way we did in the Base Scenario.

4.4 Case study results

Table 11 presents the results of our Case Study considering cooperation and no cooperation between Movistar, Claro, and Tigo. Among the three operators' users, there were 38,441 services being demanded. Without cooperation, only 31,155 of those connections were satisfied, but thanks to our lexicographic model for cooperation, this number raises to 34,940 under a cooperation scenario, achieving an increase on the overall service level of 12.14% (i.e., $(34,940 - 31,155)/31,155$).

From Table 11 it is also possible to evidence there is a tradeoff between the service level and the overall cost. Without cooperation, the overall cost of the connections is $43,673.82. Nevertheless, when cooperating, those 34,940 services can be connected at a minimum cost of $67,149.82, representing a cost of a cooperative policy 53.75% higher.

Table 11: 2-Phase results on the case study with and without cooperation

	Without Cooperation		With Cooperation	
Phase	Phase 1	Phase 2	Phase 1	Phase 2
Possible Connections	38441			
Assigned Connections	31155		34940	
Lost Connections	7286		3501	
Service Level	81.05		90.89	
Total Cost	$46297.42	$43673.82	$316303.31	$ 67149.82

Table 12 presents the roaming income, cost and profit for every operator in every phase of our lexicographic approach for cooperation. As noted, the model is effectively reducing costs from phase 1 to phase 2 for every operator, which can be interpreted in the creation of possible roaming revenues for all the operators. Although Movistar and Tigo do not have a positive roaming profit, they significantly increased from phase 1 to phase 2 of the model as well. Likewise, Claro is the one operator that receives the most income for the provision of the service. Considering that this operator has the most antennas in the area, it is also the one with the greatest capacity to provide roaming service to the other operators.

Table 12: Roaming income, cost, and profit for every operator in the case study

	Phase 1			Phase 2		
Operator	Movistar	Claro	Tigo	Movistar	Claro	Tigo
Roaming Income	71051.9	144830.83	83815.98	3871.47	11907.09	7224.43
Roaming Cost	114024.19	76404.64	109269.88	10699.23	4685.38	7618.38
Roaming Profit	-42972.29	68426.18	-25453.89	-6827.76	7221.71	-393.95

Table 13 presents the total number of connections required by the users with a contractual relationship with every operator, as well as the number of connections accomplished with and without cooperation in our Case Study. For the Movistar, the number of connections increased from 9,505 to 11,704 services, which represents an increase in the service level of 23.135%,; for Claro, it changed from 11,979 to 12,218 connections, increasing service level in 1.995%; and finally, for Tigo, it changed from 9,671 to 11,018, increasing its service level in 13.928%.

As we did in the Base Scenario, we also analyzed every operator's marginal connection's cost and profit in our Case Study. Table 14 presents these values. It clearly shows that Claro has the highest cost of establishing a new roaming connection, while Movistar and Tigo have similar marginal costs. However, even with a high marginal cost, Claro obtains great profitability on cooperation agreements,

Table 13: Number of connections supplied on models with and without cooperation

Operator	Total Connections Required	Connections accomplished without cooperating	Connections accomplished cooperating
Movistar	12739	9505	11704
Claro	13025	11979	12218
Tigo	12677	9671	11018

obtaining average profitability of $ 30.22 for each additional connection established to non-owned infrastructure.

Table 14: Marginal cost and profit for an additional connection using roaming

Operator	Cost Additional Connection	Profit Additional Connection
Movistar	4.87	-3.1
Claro	19.6	30.22
Tigo	5.66	-0.29

As noted, all three operators obtain certain benefits by cooperating with our lexicographic approach: some, like Movistar and Tigo, do not have utility for the provision of their antennas, however, they significantly increase their service level; other, i.e., Claro, does not have a great increase in its level of service, however, allowing cooperation represents a new income that translates into a positive utility. The previous analysis added to the fact that a better service is offered to the Colombian population, since coverage can be offered in more areas of the country without abusing the prices for the service, is a significant improvement of the current operation drawn from our lexicographic approach. Finally, when considering the profit for an additional connection over roaming as the real connection cost of an additional user, Movistar increases its original connection cost by 210% (i.e., $(1 - 3.1)/1$); Tigo decreases its cost by 71% (i.e., $(1 - 0.29)/1$); and Claro has a profit for those additional connections. All this considering a local antenna connection cost of $1.

5 Conclusions and future work

In this work, we present a lexicographic optimization model that allows the study of cooperation strategies among telecommunications operators composed of two phases: the first phase successfully maximizes the number of services attended and the second phase minimizes the overall cost of such connections. This model was conceived from a macroscopic perspective and does not consider individual interests of Telcos but aims to benefit both consumers and Telcos operation viewed as a whole. Nevertheless, many of the optimization model parameters can be modified to analyze granular cases where decision making can be critical to a company.

We demonstrated the applicability of our lexicographic model by applying it on a Base Senario and a real-world Case Study in in Colombia. From those analyses, the model successfully allowed to understand and review how possible increases in QoS would impact not only the cost but the profit of performing said cooperation. We successfully found a method where Telcos can outperform VMO with seamless roaming connectivity for users without having a significant impact on the cost to achieve this goal. The model's design allows for new competitors to contribute as much infrastructure capabilities as they would like while allowing all other operators to decide how much to charge certain new competitors. This makes this model available for potential growth without changes to its structure and makes its implementation significantly easy in any region where there exists an interest in cooperation.

Finally, the model results could also help to redistribute future investment on new infrastructure, which could allow better attention to Telcos, clients, lower costs on roaming for clients using other Telcos infrastructure, or even to create new sources of income to the company. With this in mind, new entrants to the market could even have dedicated business lines to infrastructure only in countries where this is not currently happening.

After considering all the successful results previously presented, we have identified two possible lines of research to extend this work. The first line could be to implement a dynamic approach to study its performance over time. This could potentially provide enough information to perform the least amount of connections while maintaining a certain level of QoS while reducing operation cost for Telcos. The line of research could be to consider the game theory behind the decisions of the Telcos.

Author contributions

Francisco J. MacAllister and Laura Maya formulated the model and programmed and ran the computational experiments. Jorge A. Huertas and Carlos Lozano-Garzón advised the project. Yezid Donoso was the investigation project director. The latter three authors contributed guiding and reviewing the investigation. All authors contributed to the paper.

Conflict of interest

The authors declare no conflict of interests.

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