A Multi-objective Optimization Approach for Designing Multihop Cellular Networks

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Abstract. A proper design of multi-hop cellular networks (MCNs) is a key step before its deployment. It helps determining where to install the nodes and how to configure their interfaces while guaranteeing full user coverage and satisfying traffic and QoS requirements with minimum cost. Few proposals can be found in the open literature that deals with the MCN design problem. Furthermore, these proposals assume the existence of a physical topology where the locations of the nodes are fixed. In this paper, we consider the design of MCNs assuming unfixed topologies (i.e., locations of nodes are not known a priori). We start with proposing a new multi-objective optimization model for designing MCNs. This model simultaneously optimizes two conflicting objectives, namely network deployment cost and throughput while guaranteeing users' full coverage and the requirements of providers (expected amount of traffic/users and QoS). To resolve the optimization problem, we start with an exact resolution using CPLEX, and then we develop a fast and simple greedy algorithm.

Keywords: Multihop, Cellular Networks, Design problem, Multi-objective optimization.

1 Introduction

In the last decades, several applications have emerged and have been taking more space and importance in our lives, such as multimedia applications. Indeed, the exponential growth of mobile telephony, among others, has created a huge need for new services. These services have specific requirements in terms of bandwidth and Quality of Service (QoS). Thus, wireless networks, especially cellular networks, should be designed to support these requirements. In cellular networks, data rates noticeably vary depending on the positions of users in the cell due to signal fluctuations and interferences. In addition, the quality of the received signal is much more affected by path attenuation, mainly in the case of non-line-of-sight. The capacity and the coverage are two major challenges in cellular networks. So a new architecture that solves these problems will certainly be of great interest. Multihop Cellular Networks (MCNs) has been proposed as an attractive solution [1]. This architecture consists of using relay stations (RS) that work as intermediate nodes of communication to receive and transmit data to the destination. In some cases, when necessary and when conditions permit, users themselves may act as relays. Otherwise,

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relaying is performed by dedicated equipments that are part of the network infrastructure. Thus, the communication can be carried over multiple hops instead of a single hop between a mobile station (MS) and a base station (BS). The MCNs emerged mainly in order to improve the performance and cells capacity of cellular networks. Each MS has 2 interfaces: a 3G interface to communicate directly with BSs and a WiFi interface to communicate with RSs; each RS has a 3G interface to communicate with BSs and a WiFi interface to communicate with MSs and neighbouring RSs. It has been shown [1] that MCNs reduce interference and provide better coverage and higher throughput.

Major research efforts have been focused on developing design solutions for cellular networks and WLANs. However, we can’t apply these solutions because these networks strongly differ from MCNs (e.g., 1-hop communication vs. multiple-hop communication). The design of a MCN basically involves choosing the best installation location (given a set of candidate locations), the type of network nodes to install (Base Station “BS” or Relay Station “RS”) and their number. It involves also deciding the channels or codes to be assigned and the power to be applied to nodes’ interfaces while at the same time providing guaranteed coverage to users and adequate connectivity with minimum cost.

Most of related work on the performance improvement of MCNs assumes a fixed topology. In fact, in the open literature, we came across several contributions that compute the throughput for a given MCN topology and node locations [7- 9]. It has been proved that the number of deployed RSs has an impact on the performance of the network. In this context, the impact of the cell radius and the number of relays in the system performance was studied and evaluated in [2]. A number of existing contributions assume that the relay stations are pre-installed and try to optimize some parameters, such as traffic load [12] and delay [13]. Contributions in [3-5] studied the most convenient locations of BSs in a cellular environment without the use of RSs. So et al. [6] investigated relay placement with the assumption that the BSs are pre-installed (positions known a priori). More specifically, in the context of a single BS (i.e., cell), they proposed an approach to compute a minimum number and the best positions of relays, to use in a micro cell, in order to maintain the pre-specified uplink and downlink demands of the end users. However, this work did not consider the constraints of interferences.

The cost of deployment and throughput are the most important criteria in MCNs design. To provide better throughput, more nodes need to be deployed. However, the more nodes we use, the more expensive the deployment will be. Therefore, a single objective optimization model cannot reflect the true nature of the problem. In this paper, we define an optimization model to decide the most convenient locations for BSs and RSs simultaneously. Its objective is to minimize the network deployment cost, to maximize the network throughput, and to guarantee clients’ coverage. Our model allows the design of MCNs from scratch (e.g. a new network deployment or a new geographic area) or the expansion of existing cellular network (e.g. to increase the capacity). In opposition to existing schemes, we address several issues (e.g., multi-channel, placement of BSs, placement of RSs, and interferences) at the same time by exploiting the relationship between them.

Since the problem is NP-hard, exact solutions, using for example CPLEX, are not feasible for realistic size networks. Thus, we propose a simple heuristic to produce a feasible solution (a solution that satisfies all the constraints). Our model takes into account physical interference to make it more realistic. . The complexity of the studied problem makes the model hard and non-linear. After linearization, we solved the problem using CPLEX. Then, we proposed a greedy heuristic for larger instances. It aims at placing RSs and BSs in the most appropriate position sites to guarantee wireless connectivity and users' coverage at a minimum cost.

The key contributions of the paper can be summarized as follows: (1) a novel multi-objective optimization model that optimizes two conflicting objectives: cost and throughput. It can be used for both deployment of new MCN and expansion of an existing MCN; and (2) a heuristic algorithm to solve the model for real-size networks.

The paper is organised as follows. In Section II, we present the proposed mathematical formulation of the MCNs design problem. In Section III we describe the approach used to solve the proposed model. Section IV summarizes our preliminary experimental results. Finally, Section V concludes the paper and presents future works.

2 Problem Definition and Formulation

2.1 Problem Description

A MCN consists of a number of BSs and RSs. To relay communications between MSs and BSs, RSs are linked to BSs through wireless links; they are also interlinked through wireless links. However, BSs are interlinked using wired connections. RSs have the same structure as BSs, but they are smaller and less costly since they provide far less functionalities than BSs. The MCN can use 2 different types of RSs: fixed or mobile.

In our model, we consider a wireless network with fixed RSs, multiple channels and multiple heterogeneous radios. Each node (BS, RS or MS) has 2 interfaces: a 3G (UMTS) and a WiFi interface to use according to the available resources and the distance between the sender and the receiver. We use WiFi radio if the distance and the capacity allow it; otherwise, we use the 3G interface. Each node has multiple wireless channels (12 channels in IEEE 802.11a) which are orthogonal to each other, and multiple orthogonal codes for 3G interface (W-CDMA: Wideband Code Division Multiple Access), to allow simultaneous communications.

Let S be the set of potential sites (PS) (positions where BSs or RSs can be installed); and P the set of positions of traffic concentration in the area of study called traffic spots (TS). The design problem aims at: (a) selecting a subset $N \subseteq S$ of PSs where nodes (BSs or RSs) should be installed. This means that these nodes cover the considered TSs, and their capacities can satisfy clients' request; (b) selecting a subset $B \subseteq S$ of BSs among PSs, where the connectivity is assured and all traffic generated by TSs can find a way to reach one of these BSs; and (c) maintaining the cardinalities of N and B small enough to satisfy the financial and the performance' requirements of the network planner.

2.2 Terminology

Before going any further, we describe the terminology that will be used to define our model (see Table 1).

Table 1. Inputs

Variables	Description
c_i^b	The installation cost of BS_i , $i \in S$
c_i^r	The installation cost of RS_i , $i \in S$
$d(i, j)$	The distance between two nodes i and j
TRWifi	The maximum transmission range of WiFi interface
TR3G	The maximum transmission range of 3G interface
α_{ij}	Coverage matrix. α_{ij} = 1 if 2 devices are installed in the positions PS_j and PS_i and can communicate with each other (given the devices maximum transmission range), or if 1 device is installed in the position PS_j and can communicate with a TS_i; 0 otherwise. $i \in P \cup S, j \in S$
α_{ij}^{Wifi}	Coverage matrix with respect to WiFi. α_{ij}^{Wifi} = 1 if 2 devices are installed in the positions PS_j and PS_i and can communicate with each other (given the devices maximum transmission range of WiFi signal), or if 1 device is installed in the position PS_j and can communicate with a TS_i via WiFi signal; 0 otherwise. $i \in P \cup S, j \in S$
α_{ij}^{3G}	Coverage matrix with respect to 3G. α_{ij}^{3G} = 1 if 2 devices are installed in the positions PS_j and PS_i and can communicate with each other (given the devices maximum transmission range of 3G signal), or if 1 device is installed in the position PS_j and can communicate with a TS_i via 3G signal; 0 otherwise. $i \in P \cup S, j \in S$
φ_{ij}	Traffic capacity matrix of the wireless links. $i \in P \cup S, j \in S$
θ_i	Traffic generated by TS_i , $\forall i \in P$ θ_i should verify the following constraint: $\theta_i < \sum_{j \in S} \varphi_{ij}$
P_{max}	The maximum transmission power of MS

Table 1. (*Continued*)

Power_WiFi	The discrete set of the power values that a WiFi radio can use
p_{ij}^{3G}	Received power (3G signal) from TS_i or PS_i to PS_j
P_i^{3G}	Transmission power (3G signal) of TS_i or PS_i
P_i^{WiFi}	Transmission power (WiFi signal) of TS_i or PS_i
TR_i	Transmission range of node i
TR_i^{3G}	Transmission range of node i using 3G interface
TR_i^{Wifi}	Transmission range of node i using WiFi interface
f_{ij}^k	Traffic flow routed from TS_i or RS_i to BS_j or RS_j using k
f_{ij}^c	Traffic flow routed from TS_i or RS_i to BS_j or RS_j using code c
x_{ij}	A binary variable that takes 1 if TS_i is assigned to PS_j; 0 otherwise
r_j	A binary variable that takes 1 if a RS is installed in PS_j; 0 otherwise
b_j	A binary variable that takes 1 if a BS is installed in PS_j; 0 otherwise
t_i	A binary variable that takes 1 if TS_i can transmit its traffic to RS/BS; i.e. if TS_i is covered by one or more PSs
y_{ij}^k	A binary variable that takes 1 if there exists a wireless link between PS_i and PS_j or between TS_i and PS_j which uses channel k; 0 otherwise
z_{ij}^c	A binary variable that takes 1 if there exists a 3G connection between 2 PS i and j or between TS_i and PS_j which uses code c; 0 otherwise
u_{ij}	A binary variable that takes 1 if node j is the farthest node from i such that $y_{ij} = 1$; 0 otherwise

2.3 Mathematical Formulation

The objective functions aim at minimizing the cost of the infrastructure deployment and maximizing the throughput of network. We define three objective functions.

Objective Functions

$$\max \sum_{k\le N}\sum_{i\in S\cup P}\sum_{j\in S}\frac{f_{ij}^{k}}{\varphi_{ij}} \tag{a}$$

$$\min \sum_{i\in S\cup P}\sum_{j\in S}\frac{p_{ij}^{3G}}{P_{\max}} \tag{b}$$

$$\min \sum_{i\in S} C_i^b b_i + C_i^r r_i \tag{c}$$

where (a) maximizes the flow capacity ratio of WiFi links to maximize WiFi throughput; (b) minimizes the power received by the nodes (RSs and BSs) to limit interferences and cell overlapping to maximize 3G throughput; and (c) minimizes the deployment cost.

In this paper, we convert this multi-objectives model to an aggregated form using a single objective model by using a weighted sum of the three objectives. The goal is to resolve the model using common single objective resolution methods. In future work, we plan to resolve the proposed model using multi-objective resolution methods [14].

$$\min(\alpha_1 * \sum_{i\in S}(C_i^b b_i + C_i^r r_i) + \alpha_2 * M * \sum_{i\in S\cup P}\sum_{j\in S}\frac{p_{ij}}{P_{\max}} - \alpha_3 * M' * \sum_{i\in P\cup S}\sum_{j\in P}\sum_{k\le N}\frac{f_{ij}^{k}}{\varphi_{ij}})$$

where $\alpha_1 + \alpha_2 + \alpha_3 = 1$, and $M \in \Re^+$ is a penalty coefficient.

M' must respect this constraint: $M' \ge 10^6 * \sum_{i\in S}(C_i^b + C_i^r)$.

In our model, $M = M' = 10^7$.

Constraints

$$\sum_{j\in S}\alpha_{ij} * (r_j + b_j) \ge t_i \qquad \forall i\in P \tag{1}$$

$$x_{ij} \le \alpha_{ij} * (r_j + b_j) \qquad \forall i\in P\cup S, \forall j\in S \tag{2}$$

$$r_j + b_j \le 1 \qquad \forall j\in S \tag{3}$$

$$\sum_{j\in S} x_{ij} \ge t_i \qquad \forall j\in P \tag{4}$$

$$f_{ij}^{k} \le \varphi_{ij} * y_{ij}^{k} \qquad \forall i\in S\cup P, \forall j\in S \qquad \forall k\le N \tag{5}$$

$$\sum_{k\le N}\sum_{\substack{j\in S\\ j\notin P}} f_{ij}^{k} + \sum_{c\le L}\sum_{\substack{j\in S\\ j\notin P}} f_{ij}^{c} + f_i = \sum_{k\le N}\sum_{l\in S\cup P} f_{li}^{k} + \sum_{c\le L}\sum_{l\in S\cup P} f_{li}^{c} \qquad \forall i\in S\ (i\notin P) \tag{6}$$

$$\sum_{k\le N}\sum_{\substack{j\in S\\ j\notin P}} f_{ij}^{k} + f_{ij}^{c} \le M_1 * r_i \qquad \forall i\in S\ (i\notin P) \tag{7}$$

$$\sum_{k\le N}\sum_{l\in S\cup P} f_{li}^{k} + f_{li}^{c} \le M_1 * (r_i + b_i) \qquad \forall i\in S \ \ (i\notin P) \tag{8}$$

$$\sum_{k\le N}\sum_{j\in S} f_{ij}^{k} + \sum_{c\le L}\sum_{j\in S} f_{ij}^{c} = \theta_i * t_i \qquad \forall i\in S \ \ (i\notin P) \tag{9}$$

$$\theta_i + \sum_{k\le N}\sum_{j\in S} f_{ij}^{k} + \sum_{c\le L}\sum_{j\in S} f_{ij}^{c} = \sum_{k\le N}\sum_{l\in S\cup P} f_{li}^{k} + \sum_{c\le L}\sum_{l\in S\cup P} f_{li}^{c} \qquad \forall i\in P\cap S \tag{10}$$

$$\sum_{j\in S\cup P}\sum_{k\le N} f_{ji}^{k} + \sum_{j\in S\cup P}\sum_{c\le L} f_{ji}^{c} - f_i \le M_2 * (1-b_i) \qquad \forall i\in S \tag{11}$$

$$f_i \le M_2 * b_i \qquad \forall i\in S \tag{12}$$

$$\frac{p_{ij}^{3G}}{g_{ij}} \le P_{\max} \qquad \forall i\in S\cup P, \forall j\in S \tag{13}$$

$$P_i^{3G} \le M * \sum_{c\le L}\sum_{j\in S} z_{ij}^{c} \qquad \forall i\in P\cup S \tag{14}$$

$$p_{ij}^{3G} \le M_4 * f_{ij}^{c} \qquad \forall i\in S\cup P, \forall j\in S \tag{15}$$

$$P_i^{3G} \le M * \sum_{c\le L}\sum_{j\in S} z_{ij}^{c} \qquad \forall i\in P\cup S \tag{16}$$

$$\frac{\dfrac{P_i^{WiFi}}{d(i,n)^{\lambda}}}{\mu + \dfrac{P_m^{WiFi}}{d(m,n)^{\lambda}} * y_{mn}^{k}} * y_{in}^{k} \ge SIR_{\min} \qquad \forall i,m\in P\cup S, \forall n\in S, \forall k\le N \tag{17}$$

$$P_i^{WiFi} \in Power\_Wifi \qquad \forall i\in P\cup S \tag{18}$$

$$P_i^{WiFi} \le M * \sum_{k\le N}\sum_{j\in S} y_{ij}^{k} \qquad \forall i\in P\cup S \tag{19}$$

$$r_i \le \sum_{x}\sum_{y}\sum_{j\in S} \alpha_{i_x j} b_j \alpha_{i_x i_y} \qquad \forall i_x, i_y \in S\,;\, x,y\in \aleph \tag{20}$$

$$f_{ij}^{k} \le M_4 * y_{ij}^{k} \tag{21}$$

$$y_{ij}^{k} \le f_{ij}^{k} \tag{22}$$

$$f_{ij}^{c} \le M_5 * z_{ij}^{c} \tag{23}$$

$$z_{ij}^{c} \le f_{ij}^{c} \tag{24}$$

$$t_i \le \sum_{j\in S} \alpha_{ij} \qquad \forall i\in S\cup P \tag{25}$$

$$\sum_{j\in S} \alpha_{ij} \le M_6 * t_i \qquad \forall i\in S\cup P \tag{26}$$

$$y_{ij}^{k} \le \alpha_{ij}^{Wifi} \qquad \forall i\in P\cup S \tag{27}$$

$$z_{ij}^{c} \le \alpha_{ij}^{3G} \qquad \forall i\in P\cup S \tag{28}$$

$$f_{ij}^{k}, f_{ij}^{c}, f_i, M_1, M_2, M_3, M_4, M_5 \in \Re^{+} \tag{29}$$

$$x_{ij}, r_i, b_i, y_{ij}^{k}, y_{ij}, z_{ij}^{c}, z_{ij}, u_{ij}, e_{ij} \in \{0,1\} \tag{30}$$

Constraint (1) ensures that each TSi is covered by at least one RS or BS. Constraint (2) ensures that TSi or PSi can be assigned to PSj only if one RS or one BS is installed in PSj and this node covers TSi or PSi. Constraint (3) prevents to have RS and BS installed in the same PSj. Constraint (4) stipulates that each TSi should be assigned to at least one PSj. Constraint (5) prevents a link flow from exceeding the capacity of the link; it also states that a link between 2 nodes i and j using a channel k can exist only if there are 2 nodes installed there, connected and assigned the same channel. Constraints (6) - (10) define the flow balance for each node. Since we consider only the uplink, the flow received by a BS doesn't go out. This traffic is absorbed locally using a new variable f_i which is defined by constraints (11) and (12). Constraint (13) ensures that the emission power of a node cannot exceed the maximum emission power (Pmax). Constraint (14) states that if there is no 3G connection between two nodes i and j, P_i^{3G} must be equal to zero. Constraint (15) forces p_{ij}^{3G} to be equal to zero when there is no flow between two nodes i and j. Constraint (16) forces p_i^{3G} to be equal to zero when there is no flow between node i and other nodes. Constraints (17) and (18) limit the interference on WiFi link. We use a physical model of interference [9] since it is more realistic than a logical model. For example, if $y_{mn}^{k} = 1$ (there exists a wireless link between PSm and PSn or between TSm and PSn which uses channel k) and constraint (17) is satisfied, then a successful transmission is feasible between PSi and PSn or TSi and PSn. For each node i, the smallest value in Power_WiFi that satisfies (17) is selected (constraint (18)). Constraint (19) forces P_i^{WiFi} to be equal to zero when there is no flow between node i and any other node. Constraint (20) stipulates that each node must reach at least one BS via one or multiple hops. Note that this condition is already covered by the flow conservation (6)-(10) and the sink constraints (11)-(12). The traffic must start from MS to reach one BS. It is generated by MS if this MS is covered by one PS (constraints (10) and (11)); in this case, the traffic traverses several nodes (constraint (6)) until it reaches one BS (constraints (7)-(9)). So, these constraints guarantee that every MS is linked to a BS. Constraints (21)-(24) state that when there is no WiFi link (respectively 3G link) between two nodes i and j ($y_{ij}^{k} = 0$, $z_{ij}^{c} = 0$), the flow must be equal to zero ($f_{ij}^{k} = 0$, $f_{ij}^{c} = 0$); and inversely, when the flow between two nodes i and j is equal to zero, that means there is no WiFi link between these two nodes. Constraints (25) and (26) stipulate that for each node i, if there is no node that covers it ($\sum_{j \in S} \alpha_{ij} = 0$), then the traffic cannot be sent ($t_i = 0$); and inversely, if we can't send the traffic of a node i to another node, that means there is no node that covers i. Constraint (27) (resp. constraint (28)) is logical constraint to relate the WiFi (resp. 3G) coverage to the existence of wireless link between two nodes i and j.

Metrics

p_{ij}^{3G} computes the received power from TS$_i$ or PS$_i$ to PS$_j$ [11]

$$p_{ij}^{3G} = \frac{1}{1+\frac{W}{(\frac{E_b}{N_0})*R*v_i}} * I_{total} \text{ if } \exists c \,/\, z_{ij}^{c} \neq 0; \qquad p_{ij}^{3G} = 0 \quad \text{otherwise} \tag{31}$$

where W is the WCDMA chip rate which is equal to 3.84 Mcps, R is the bit rate of user i, v_i is the activity factor of user i at physical layer (the recommended values of this variable are 0.67 for speech and 1.0 for data), $\frac{E_b}{N_0}$ is the energy per user bit divided by the noise spectral density, and I$_{total}$ is the total received wideband power including thermal noise power in the base station. I$_{total}$ is formulated as follows:

$$I_{total} = \sum_{i \in F} P_i^{3G} + \eta \tag{32}$$

where F represents the set of nodes i that transmit to the same BS or RS.

g$_{ij}$ used in constraint (15) is the propagation factor of the radio link between TS$_i$ and PS$_j$ or PS$_i$ and PS$_j$:

$$g_{ij} = \frac{1}{10^{\frac{A(d(i,j))}{10}}} \tag{33}$$

where A(d(i.j)) represents the channel attenuation (in dB) [17]. In this formula d(i,j) must be expressed in Km.

$$A(d(i.j)) = \begin{cases} 143.83 + 38.35 * \log(d(i,j)) \text{ for urban areas} \\ 116.31 + 38.35 * \log(d(i,j)) \text{ for rural areas} \end{cases} \tag{34}$$

The received power of each node i is computed as follows:

$$P_i^{3G} = \max_{j \in S} p_{ij}^{3G} \qquad \forall i \in P \cup S \tag{35}$$

Equations (36) and (37) compute transmission range of WiFi and 3G interfaces respectively. The transmission range of node i consists of the distance between this node and the farthest node j with which it communicates ($\exists k, f_{ij}^{k} \neq 0$ or $\exists c, f_{ij}^{c} \neq 0$).

$$TR_i^{Wifi} = \max_{j \in P}(d_{ij} * y_{ij}^{k}) \qquad \forall i \in P \cup S, k \leq N \tag{36}$$

$$TR_i^{3G} = \max_{j \in P}(d_{ij} * z_{ij}^{c}) \qquad \forall i \in P \cup S, c \leq L \tag{37}$$

Model linearization

Constraints and metrics (17), (31), (35), (36) and (37) are not linear. In the following, we propose an approach to make them linear. The goal is to produce a linear model for MCN design.

We replace constraint (17) by the following constraints:

$$p\_y_{ij}^{k} \le M * y_{ij}^{k} \qquad \forall i \in P \cup S, j \in S, k \le N \tag{17-1}$$

$$p\_y_{ij}^{c} - P_i^{WiFi} \le 1 - y_{ij}^{k} \qquad \forall i \in P \cup S, j \in S, k \le N \tag{17-2}$$

$$p\_y_{ij}^{k} - P_i^{WiFi} \ge M * (y_{ij}^{k} - 1) \qquad \forall i \in P \cup S, j \in S, k \le N \tag{17-3}$$

$$\frac{\frac{p\_y_{in}^{k}}{d(i,n)^{\lambda}}}{\mu + \frac{p\_y_{mn}^{k}}{d(m,n)^{\lambda}}} \ge SIR_{\min} \qquad \forall i,m \in P \cup S, n \in S, k \le N \tag{17-4}$$

where $p\_y_{ij}^{k} = \begin{cases} P_i^{WiFi} & if \quad y_{ij}^{k} = 1 \\ 0 & if \quad y_{ij}^{k} = 0 \end{cases}$

We replace constraint (31) by the following constraints:

$$p\_z_{ij}^{c} \le M * z_{ij}^{c} \qquad \forall i \in P \cup S, j \in S, c \le L \tag{31-1}$$

$$p\_z_{ij}^{c} - P_i^{3G} \le 1 - z_{ij}^{c} \qquad \forall i \in P \cup S, j \in S, c \le L \tag{31-2}$$

$$p\_z_{ij}^{c} - P_i^{3G} \ge M * (z_{ij}^{c} - 1) \qquad \forall i \in P \cup S, j \in S, c \le L \tag{31-3}$$

$$p_{ij}^{3G} = \frac{1}{1 + \frac{W}{(\frac{E_b}{N_0}) * R * v_i}} * (\sum_{i \in F} p\_z_{ij}^{c} + \eta * z_{ij}^{c}) \qquad \forall i \in P \cup S, j \in S, c \le L \tag{31-4}$$

where $p\_z_{ij}^{c} = \begin{cases} P_i^{3G} & if \quad z_{ij}^{c} = 1 \\ 0 & if \quad z_{ij}^{c} = 0 \end{cases}$

We replace constraint (35) by the following constraints:

$$P_i^{3G} \ge p_{ij}^{3G} \qquad \forall j \in S, \forall i \in P \cup S \tag{35-1}$$

$$P_i^{3G} = p_{ij}^{3G} * e_{ij} \qquad \forall j \in S, \forall i \in P \cup S \tag{35-2}$$

$$\sum_{j \notin S} e_{ij} \le 1 \qquad \forall j \in S \tag{35-3}$$

$$\text{where } e_{ij} = \begin{cases} 1 & if \quad p_{ij}^{3G} \geq p_{il}^{3G} \quad \forall l \in S \\ 0 & else \end{cases}$$

We replace constraint (36) by the following constraints:

$$TR_i^{Wifi} \geq d_{ij} * y_{ij}^k \qquad \forall i \in P \cup S,\ j \in S, k \leq N \qquad (36\text{-}1)$$

$$TR_i^{Wifi} = \sum_{j \in S} d_{ij} * u_{ij} \qquad \forall i \in P \cup S \qquad (36\text{-}2)$$

$$\sum_{j \in S} u_{ij} \leq 1 \qquad \forall i \in P \cup S \qquad (36\text{-}3)$$

$$\text{where } u_{ij} = \begin{cases} 1 & if \quad d_{ij} * y_{ij}^k \geq d_{il} * y_{il}^m \quad \forall l \in S, k, m \leq K \\ 0 & else \end{cases}$$

We replace constraint (37) by the following constraints:

$$TR_i^{3G} \geq d_{ij} * z_{ij}^c \qquad \forall i \in P \cup S,\ j \in S, c \leq L \qquad (37\text{-}1)$$

$$TR_i^{3G} = \sum_{j \in S} d_{ij} * v_{ij} \qquad \forall i \in P \cup S \qquad (37\text{-}2)$$

$$\sum_{j \in S} v_{ij} \leq 1 \qquad \forall i \in P \cup S \qquad (37\text{-}3)$$

$$\text{where } v_{ij} = \begin{cases} 1 & if \quad d_{ij} * z_{ij}^c \geq d_{il} * z_{il}^n \quad \forall l \in S, c, n \leq L \\ 0 & else \end{cases}$$

3 Problem Resolution

In the beginning, we solved the problem using the linear solver CPLEX. However, since the problem is NP-hard, CPLEX can only solve it for small sized networks. An exact resolution is not feasible for realistic size networks. Thus, we have developed a constructive greedy heuristic to solve this problem and to obtain a good solution (not optimal) within a reasonable amount of computing time.

The heuristic inputs consist of the positions of potential sites (PSs) and traffic spots (TSs), and the expected traffic per TSs. The proposed heuristic aims at placing RSs and BSs in the most appropriate position sites. After running the proposed heuristic, we obtain, as outputs, RSs and BSs positions and their characteristics (coverage range, channel and code assignment, power applied to each node's interface, traffic received and sent by each node and the paths traffic traverse from TSs to BSs).

The operation of the proposed heuristic consists of 2 steps: (1) RSs are first placed since they are cheaper and they are biased towards multi-hop communications; and (2) BSs are installed. Step (1) takes into account the objective functions (a) and (b). It satisfies the constraints of coverage and interference. This step includes two sub-steps: (a) RS_j is placed in PS_j if there exist TS_i covered by only one PS_j, and if there is enough resources to satisfy TS_i demand; and (b) for each PS_j, a set E_j is created of TSs which are not yet assigned to any RS, and covered by this PS_j. Then, these sets E_j

are sorted in decreasing order of their cardinalities. Next, the first set E_j is considered and then a RS is installed in PS_j. All TSs$\in E_j$ are assigned to this RS while satisfying resource and interference conditions. After that, the TSs belonging to more than one set E_j and have been already assigned, are removed from the others sets E_k. The process (1-b) is repeated until all TSs are assigned.

The main objective of Step (2) is to ensure that each node can reach at least one BS via one or multiple hops. This step includes two sub-steps: (a) a RS is replaced by a BS if it is not covered by any other RS or PS to ensure that each MS can reach one BS in one hop or more; note that the maximal number of hops n to reach a BS from a TS must be limited since the verification of the solution feasibility does not scale with the number of hops (in our simulations, n assumes 2); and (b) next, for each RS_j, a set F_j, that consists of covered RSs, is created. The sets F_j are sorted in decreasing order of their cardinalities. The first set F_j is considered and then RS_j is replaced by a BS_j. All RSs$\in F_j$ are assigned to this BS while satisfying interference and capacity constraints. The RSs belonging to more than one set F_j and have been already assigned, are removed from the other sets F_k. The process (2-b) is repeated until all F_k are processed. If there are RSs not assigned to BSs or to other RSs, we add BSs in the appropriate position sites (we mean by that, we repeat step (2) by creating sets of RSs not yet assigned and in the range of PSs instead of other RSs, then install BS in PS when necessary). The pseudo-code of the proposed greedy algorithm (GA) is shown in Algorithm 1.

Algorithm 1. Greedy – Main

```
Input    : positions of PSs and TSs; TSs' traffic
Output   : positions of RSs and BSs, nodes' transmission range, channel assignment
Step 1
a-  for each $TS_i$ covered by only one PSj do
        if available resources satisfy $TS_i$ demand then
            place $RS_j$ in $PS_j$
            assign the appropriate channel
    end if
    end for
b-  for each $PS_j$ do
            create a set $E_j$
        end for
        sort $E_j$ in decreasing order of their cardinalities
        consider the first set $E_j$ , install $RS_i$ in $PS_j$
        for each TS$\in E_j$ do
            if available resources satisfy TS' demand then
                assign TS to $RS_i$
                assign the appropriate channel
                for each $E_k$ such that $k \neq i$ do
                    if TS$\in E_k$ such that $k \neq i$ then
                        remove TS from $E_k$
                    end if
                end for
```

```
            end if
          end for
c-   repeat the step (1-b) until all TSs are assigned

Step 2
a-   for each $RS_i$ do
            if $RS_i$ not covered by any $RS_k$ such that $k \neq i$ then
               replace $RS_i$ by $BS_i$
            end if
          end for
b-   for each $RS_j$ do
            create a set $F_j$
         end for
     sort $F_j$ in decreasing order of their cardinalities
         consider the first set $F_j$ , replace $RS_j$ by $BS_j$
     for each $RS \in F_j$ do
            if available resources satisfy RS' demand then
               assign RS to $BS_j$
               assign the appropriate channel
               for each $F_k$ such that $k \neq i$ do
                   if $RS \in F_k$ then
                      remove RS from $F_k$
                   end if
               end for
            end if
       end for
c-   repeat the step (2-b) until all RSs are assigned

Step 3
     for each node i do
         compute the transmission range of  i
     end for
```

In this study, channels are divided in two groups: channels to handle traffic between TSs and RSs or TSs and BSs, and channels used to relay traffic from RSs to other RSs or to BSs. In the case of 3G, we divide the codes similarly in two groups: codes serving to handle traffic between TSs and RSs or TSs and BSs, and codes used to relay traffic from RSs to other RSs or to BSs.

4 Experimentations and Results Analysis

4.1 Experimentation

In this paper, we suppose that the codes are orthogonal and there is no interference in 3G links. In our experiment, the positions of PSs and TSs, and the traffic of each TS are randomly generated. The installation cost of a BS is 5 times bigger than the cost of a RS installation due to the functionalities offered by the BSs compared to RSs and their capacities. We use two radio interfaces (WiFi and 3G) with capacities of 54 Mbs and 2 Mbs respectively (that means each value in matrix φ_{ij} is equal to 54). The number of channels is 12 and the number of codes is 256. The algorithm is coded in C++ programming language.

4.2 Results and Analysis

In this section, we study the performance of the proposed greedy algorithm by comparing its results with those given by CPLEX.

In this study, we increase gradually the number of candidate locations while all other parameters are maintained fixed. We solve the problem for medium size instances ($\leq 1.5km * 1.5km$) using (a) CPLEX and (b) the greedy algorithm, then we compare the objective values returned by each solver. For each problem size, we generate randomly 10 different instances. Fig. 1 shows the average of the objective values obtained by CPLEX and the proposed greedy algorithm with the number of TS.

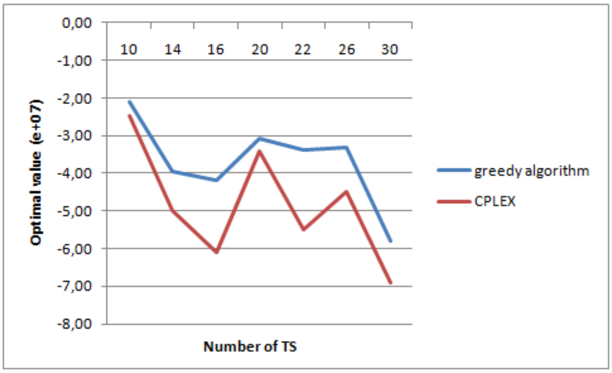

Fig. 1. Comparison between results given by both solvers

"Optimal value" means the best value of the objective function obtained by resolving the problem. In our case, since we try to minimize, more the optimal value is small, more the result is satisfying.

Comparing the results yielded by CPLEX with those obtained by our greedy algorithm, we observe that CPLEX produces smaller objective values (thus better solutions); however, the greedy algorithm produces results that are not too far from the optimal results (returned by CPLEX). In conclusion, the proposed algorithm returns acceptable solutions; this being said, we developed the greedy algorithm just to show the feasibility of the model; we plan to develop more sophisticated resolution methods that produce near optimal solutions.

For 30 TSs, CPLEX takes approximately 6 hours to resolve the problem. However, the proposed algorithm gives a solution in few seconds even for instances of 50, 80 and 100 TSs. In these situations, CPLEX does not return solutions (i.e., response time tends to "infinity").

5 Conclusion

In this paper, we considered the MCN design problem. We proposed a multi-objective MCN design model which is unique. The goal is to minimize the total cost deployment and maximize the flow capacity ratio of the network while satisfying the coverage, the interference constraints and the user requirements. To show the validity of the model, we developed a simple heuristic to resolve the model. We are currently developing a Tabu search algorithm to produce near optimal solutions.

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