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INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

***Column generation for LTE-like network
optimization: on the capacity and energy trade-offs***

Anis Ouni — Hervé Rivano — Fabrice Valois

N° 7437

October 2010

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*R*apport
de recherche

Column generation for LTE-like network optimization: on the capacity and energy trade-offs

Anis Ouni*[†], Hervé Rivano^{‡†}, Fabrice Valois[†]

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Abstract: Multi-hop wireless networks have been receiving an ascending success these last years. Despite these networks still suffer some problems, other challenges such as network capacity are well investigated and elaborated by research community. Sometimes, for an operator, the network capacity is not only the most important aspect; energy consumption is also crucial to make profits.

In this paper, we focus in broadband wireless mesh networks like 3GPP LTE-Advanced. We propose an extended multiobjective linear model using column generation allow us to study the performance of LTE backhauling network. Based on this model we study, in first one, the Pareto-optimal set of solutions with respect to capacity and energy and , in the second one, the optimal fairness end-to-end communication rates, routing and transmission scheduling. We show that some significant engineering results found, using this model, are very similar.

Key-words: LTE, WMN, network capacity, energy consumption, linear program, multiobjective, scheduling, routing.

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Génération de colonnes pour l'optimisation de réseau de type LTE: vers l'étude de compromis capacité-énergie

Résumé : Les réseaux sans fil multi-saut ont reçu un succès croissant ces dernières années. Parmi d'autres enjeux, la capacité de ces réseaux a été bien étudié par la communauté de la recherche. Toutefois, la capacité du réseau n'est pas le seul aspect important, la consommation d'énergie est également un autre défis à prendre en considération. Dans ce travail, nous nous intéressons aux réseaux maillées sans fil de type LTE-Advanced. Nous proposons des outils basés sur un modèle linéaire multi-objectif et une génération de colonnes. Le but est de maximiser la capacité, minimiser la consommation énergétique et d'étudier le compromis entre ces deux critères. On montre qu'il n'y a pas de compromis lorsqu'on utilise des modèles simplistes. D'autres résultats d'ingénierie sont mis en oeuvre en utilisant ces outils.

Mots-clés : Réseaux Radio Maillés, capacité, routage, consommation énergétique, programmation linéaire, ordonnancement.

1 Introduction

The rapid growth of the Internet access and multimedia applications requires more bandwidth, higher data rates and quality of service. Therefore, wireless networks must be adapted to support new constraints. Wireless mesh networks (WMNs) have emerged recently as a promising technology to meet these demanding requirements. In particular, network capacity is a key element in these wireless networks. A higher capacity makes the network support more demands and provide a better quality of service. This metric is well investigated and elaborated by research community since the seminal work of Gupta and Kumar [1]. Improving the capacity is still an open research topic that interest us. On the other side, energy consumption minimization and electromagnetic pollution are main societal and economical challenges nowadays, the goal is to minimize the cost of energy consumption and to protect the environment. The main contribution of this paper is to address the optimization of both network capacity and energy consumption.

We consider a broadband wireless mesh networks like 3GPP LTE-Advanced where two traffics are operated. The first one is between stationary or mobile clients and the base station (aka eNode B: the LTE base station). The second one is between the base stations, that create a wireless backhaul topology. Each BS collects the traffic generated by the clients and forwards it through multi-hop communications toward some dedicated BS, called gateways (aka SAE GW: System Architecture Evolution) that bridge the backhauling network to the core network (fig. 1). We assume that mobile-to-eNodeB and eNodeB-to-eNodeB traffic use different and independent resources. Our study focuses on the backhauling network. We do not take into account the users requests but rather the flows aggregated by the base station.

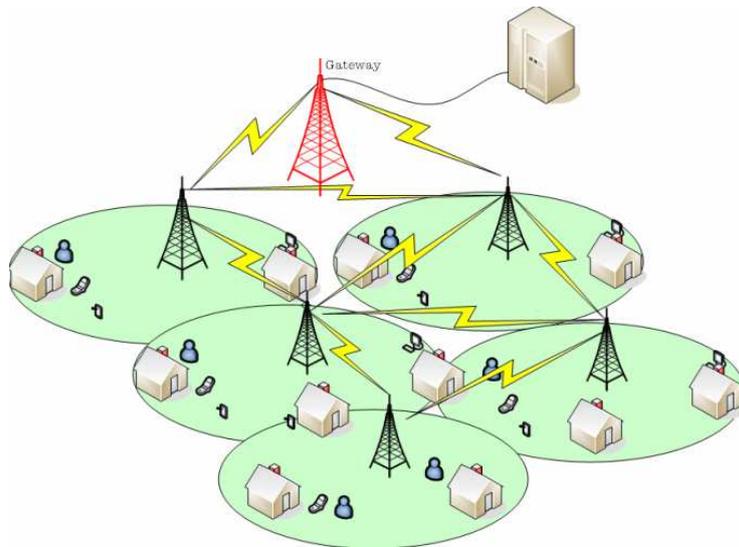


Figure 1: Wireless mesh network architecture: base stations collect the traffic from clients (mobile or static) and forward it to the core network.

In this work we investigate on the trade-offs between capacity and energy consumption minimization. This issue has been well studied on a point to point physical layer communication using Shannon theory [2, 3]. Our work pursues the same objective in network wide from the MAC and routing perspective. Our contribution is two-fold: (a) Developing a complete framework considering jointly capacity maximization with energy minimization. Note that our framework is extensible to accommodate any model of energy consumption and radio characteristics (interferences, fading, shadowing). (b) Finding an optimal system configuration and network engineering such as: capacity and energy trade-offs, optimal routing and scheduling, etc. Computing an optimal capacity of the backhaul with a minimum energy consumption is the main objective of this study. To our knowledge, we are among the first that addresses these issues.

The rest of the paper is organized as follows. Next Section reviews the related works. In Section 3 gives an overview about LTE physical layer and how to take it into account in a linear program. Section 4 is dedicated to describe the multiobjective framework based in a linear program and a column generation to solve it. Section 5 highlights key results and engineering insight obtained by using this linear program. We conclude the paper by giving future directions in Section 6.

2 Related work

Since the seminal work of Gupta [1], the evaluation of the capacity of wireless networks has received much attention and an important research effort. In [4], it is shown that the available capacity allocated to each node is reduced by a factor of $\frac{1}{n}$, where n is the number of nodes. This result is extended in [5], which evaluates the difference of capacity provided by an ad-hoc network or an hybrid network, using linear programming models. In [6], the regularity of the topology, the placement of gateways and the routing protocols are shown to have a limited impact on the capacity, which is directly bounded by a bottleneck around the gateways [7, 8].

Joint scheduling and routing optimization has been considered in many papers on wireless mesh network. In [7] a joint scheduling, routing and power control strategy is proposed. The authors have developed a computational tools using column generation to maximize the minimum throughput among all flows. They have confirmed the usefulness of the power control on the performance of multi-hop wireless networks. Other results have been given about routing, scheduling and spacial reuse. A similar problem is considered in [9] where the authors focus also in the optimal network configuration to achieve a maximum of throughput.

Other studies have addressed the scheduling problem around an access point on 802.11 networks. A Round Weighting Problem (RWP) has been studied in [10] in order to determine the minimum number of rounds (a round is any set of pairwise disjoint edges). In [8], the authors study the problem of Routing and Call scheduling in 802.11 multi-hop wireless networks. They provide an optimal framework for determining optimal routing and scheduling needed by the traffic in the network. Our work is based on a similar trend of optimization techniques: a column generation algorithm isolates the routing and scheduling models from the computation of concurrent links activations. The main novelty of the models

provided in Section 4 is the computation of time/frequency resource allocation accounting for the energy expenditure. Besides, we develop a multi-objective framework to address the tradeoff between capacity and energy consumption.

The optimization of energy consumption also has been well addressed in the literature especially in sensor networks where a sensor has a limited battery power. The energy expenditure in a node is typically dominated by the transmission unit. From the energy efficiency standpoint, the most effective solution is to put the wireless nodes in sleep mode [11]. Our model takes into account the idle consumption mode and calculates an optimal transmission number to minimize the overall energy consumption.

Some works focused on both the study of capacity and energy consumption. [2] studies energy, latency and capacity trade-offs existing in a multi-hop ad-hoc wireless network. The authors studied only a line topology with a simple energy model. The work is an analytical study and don't take into account a real interference model.

Some heuristic algorithms have been proposed in [12] to calculate the minimum number of slots allocated to communications. A power control is used to minimize overall energy consumption. Our work is more general because we addressed also the routing problem and we take into account the demand of each node. Note also that the solutions found by our framework are optimal.

3 LTE modelization

In the following, we give a brief description of LTE Physical Layer features, focusing on the scheduling and resources allocation.

LTE radio transmission is based on Orthogonal Frequency Division Multiple Access (OFDMA) for downlink communications and Single Carrier Frequency Division Multiple Access (SC-FDMA) for uplink communication. The advantage of using OFDMA is to exploit multiuser diversity and to provide more flexibility in radio resources allocation.

A LTE frame is divided in 20 time slots duration of 0.5 ms (TDD mode). Each two adjacent time slots are grouped into a sub-frame of length 1 ms. A sub-frame corresponds to a Transmission Time Interval (TTI). Each slot corresponds to 7 OFDM symbols, which is preceded by a cyclic prefix to avoid inter-symbol interference. The bandwidth corresponding to a slot (7 OFDM symbols) is subdivided into several blocks of 12 subcarriers, each of which is called Physical Resource Block (PRB). The smallest resources unit that can be allocated to a user covers a TTI of 1ms and a PRB (bandwidth of 180 khz), called scheduling bloc 'SB' (fig. 2).

In LTE-Advanced, the communication between base stations is not yet standardized. We assume that this communication is similar to those between base station and users. Nevertheless, the optimization models that we present further on are generic and can be applied to any synchronous slotted technology in which the resource is divided into time-frequency elements. One needs only to adapt the vocabulary.

Given a bandwidth available for the backhauling network, the goal is to find an optimal schedule within a minimum time frame to maximize the capacity. Our framework allocates, for each base station, the optimal number of SB in order to send its own traffic and route the traffic of the other nodes.

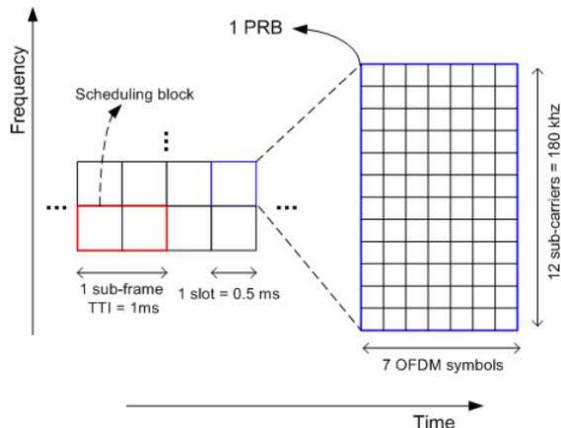


Figure 2: An illustration of resource element in LTE

4 Problem Formulation, routing and scheduling

4.1 Network model

The fixed infrastructure of the WMN can be model as a directed graph $G(V,E)$ with N static nodes representing mesh points. The set of vertices V is decomposed into two independent subsets: V_{BS} is the set of base stations ($N_{BS} = |V_{BS}|$) and V_g the set of gateways ($N_g = |V_g|$) where $N = N_{BS} + N_g$. Each base station of V_{BS} has an aggregated demand d_i that is to be routed to the gateways through multi-hop paths. We assume that the demand by each BS is static.

In the context of LTE, the network is synchronized and the time is divided into equal sized slots. In this case, it is reasonable to consider that the network is periodic with a period duration T since the demand is static. Assuming that the number of available PRB is equal to N_{RB} . Obviously, distribution of transmissions to a small number of time slots is desirable to decrease the time to improve the throughput provided to each base station. This throughput corresponds to the ratio of the volume of data sent during a period over T . The scheduling policy is to pack the maximum number of links that can be active simultaneously in each time slot. The objective is to maximize the spatial reuse of system resources and the throughput taking into account the energy consumption problem.

4.2 Link description

Given a link $(u,v) \in E$, u is the sending node and v is the receiving node. We note by (u,v,k) the communication between nodes u and v on PRB k . A link exists between two nodes if and only if they are connected. Indeed, each link $e = (u,v) \in E$ is also identified by its physical parameters:

- C_e^k : the capacity of the link e that depend of the PRB k allowed to the communication between nodes u and v .

- J_e^k : the energy consumption of the communication between nodes u and v on the PRB k . J_e^k equals to the sum of $j_t(u, v, k)$ and $j_r(u, v, k)$, the energy transmission and reception cost, respectively, on the PRB k .

4.3 Link scheduling and energy consumption

To respect the interference constraints, the links activated together must be pairwise non interfering. This generic definition allows to consider any interference model like binary models or other models based on the Signal-to-Noise-and-Interference-Ratio (SINR).

We call a configuration (noted F) a set of transmission links that can be activated together in a single slot. The set of all possible configurations is noted \mathcal{F} . A link $e = (u, v) \in F$ if and only if there exists at least a PRB k where $(u, v, k) \in F$. For sake of simplicity, a node r which is idle is denoted $r \notin F$. For each feasible configuration F , there is an energy cost $j(F)$ which is the sum of the energy cost of all active links in F and the idle cost of all remaining nodes. $j(F) = \sum_{(i,j) \in F} \sum_{k \in 1..N_{\text{PRB}}} (j_t(i, j, k) + j_r(j, i, k)) + \sum_{v \notin F} \text{Idle}(v)$, where $\text{Idle}(v)$ represents the idle energy cost for node v .

Let $W(F)$ denote the number of times that the set F is activated in the period T . In this case, the total number of slots in T is $\sum_{F \in \mathcal{F}} W(F)$ and the total communication cost is: $\sum_{F \in \mathcal{F}} W(F)j(F)$. Note that a link capacity is proportional to its activation duration in the period and equals $\sum_{F \in \mathcal{F}, F \ni e} c_e(F)w(F)$, where $c_e(F)$ is the capacity of the link e in the configuration F and equals to $\sum_{(u,v,k) \in F} c_k^e$.

We recall that network capacity represents the quantity of traffic sent by all base stations (N_{BS}) and forwarded to the core network through the gateways (K) during the period T :

$$C_{\text{network}} = \frac{\sum_{k \in K} \sum_{n \in N_{\text{BS}}} |\text{Received_packets}(n \rightarrow k)|}{T}$$

Depending on the application requirements, we can achieve a trade-offs between capacity and energy.

4.4 Flows and Routing

We study also the routing problem of the traffic demands. We denote by \mathcal{P} the set of all possible path and $f(P)$ the flow f routed on $P \in \mathcal{P}$. The goal is to route the given traffic demands of each base station to the gateways on multi-hop activated paths that minimize $\sum_{F \in \mathcal{F}} W(F)$ or $\sum_{F \in \mathcal{F}} W(F)j(F)$. A path P is activated if all its links $e \in P$ are selected enough to carry flow on them during the period T . Minimizing the network period length ensures to route the total traffic at maximum rate.

4.5 Linear model

We present a multi-objective linear program to study the trade-offs between capacity and energy consumption. Two model has been developed. The objective of the first one is to maximize the capacity subject to energy cost while satisfying the demands and capacity constraints, as described in the following linear formulation:

$$\min \sum_F w(F) \quad (1)$$

$$\forall e \in E \quad \sum_{P \in \mathcal{P}, P \ni e} f(P) \leq \sum_{F \in \mathbf{F}, F \ni e} c_e(F)w(F) \quad (2)$$

$$\sum_F w(F)j(F) \leq J \quad (3)$$

$$\forall r \in V_r \quad \sum_{P \in \mathcal{P}_r} f(P) = d(r) \quad (4)$$

The second one minimize the total energy consumption subject to capacity guarantee. As the first formulation, the variables of system are the paths $P \in \mathcal{P}$ and the configurations $F \in \mathcal{F}$.

$$\min \sum_F w(F)j(F) \quad (5)$$

$$\forall e \in E \quad \sum_{P \in \mathcal{P}, P \ni e} f(P) \leq \sum_{F \in \mathbf{F}, F \ni e} c_e(F)w(F) \quad (6)$$

$$\sum_F w(F) \leq T \quad (7)$$

$$\forall r \in V_r \quad \sum_{P \in \mathcal{P}_r} f(P) = d(r) \quad (8)$$

We observe that the number of paths and the possible configurations in the graph is exponential. Therefore these formulations cannot be manipulated with the whole set of variables when the size of the network grows. In this case, the column generation technique is efficient to resolve the problem since it avoids the enumeration of all the possible variables. For sake of space limitation, the complete description of the column generation is available in [?] and similar to these presented in [8].

5 Result analysis and discussion

5.1 Scenarios and Model Parameters

The two formulations and the column generation algorithm have been implemented and tested using the AMPL and CPLEX solver. Because of space limitation we choose to present only some results of the many scenarios we have studied. For simplicity, its assumed that for each base station the average signal-to-noise ratios (SNR) is 22dB. Noise power density is assumed -174 dBm/Hz.

All base stations operate at the same transmit power, and use the same modulation (4QAM). The channel attenuation is modeled by a path-loss with an exponent of 2.6 (Line Of Sight channel model).

A grid topology and random topology composed of $\{9, 24, 49, 121\}$ nodes, where a gateway is located in the center, are considered. The upload traffic in the network is uniformly distributed among the nodes. A distance-2 binary interference model used in which two transmissions do not interfere if there are at least two hops between them.

5.2 Network capacity, Energy cost and scalability

We present, firstly, the evolution of the optimal energy consumption and the maximum capacity obtained with the network size (from 9 to 121 nodes). Figure 3 confirms the result of decreasing of the capacity offered to base stations with the scalability of the network size [6]. The total energy consumption increases with the number of stations in the network. Adding new base stations increases the traffic load in the network, and thus, both, the period duration and the energy cost required to send it to the gateway increase. This explains the decreasing of capacity and the increasing of total energy consumption.

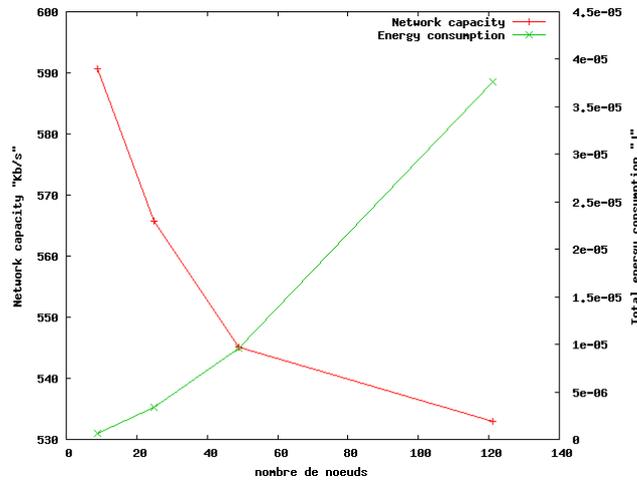


Figure 3: Capacity and energy consumption evolution vs size of the network

5.3 Capacity and energy trade-offs

In this part, we present some results about capacity and energy consumption trade-offs. Figure 4 presents the capacity/energy Pareto front for a random topology composed of 49 nodes. In this scenario we do not take into account the idle energy consumption. A first observation, we can notice two important points in the curve. Firstly, we note the existence of a minimum value of energy required to have a feasible solution. A less than this value it is not possible to meet the capacity constraint. In the second point, we show that the capacity tends to a maximum boundary. Between those two points, the capacity increases with the energy consumption.

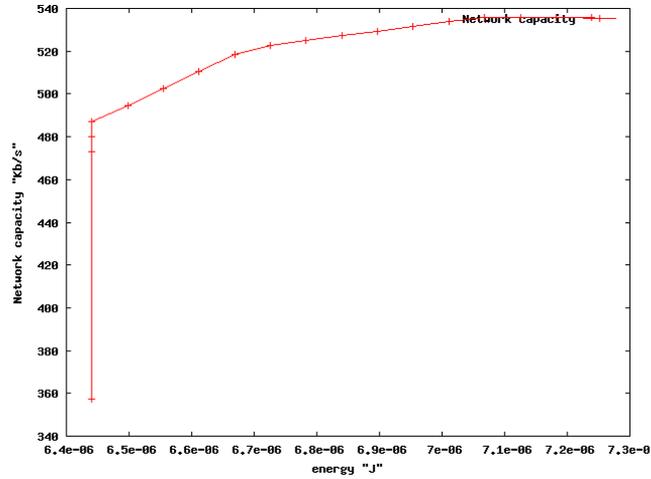


Figure 4: Capacity and energy trade-offs: Idle cost = 0.

In the second scenario, we study the trade-offs between capacity and energy consumption according to idle energy consumption values. Take into account consumption in idle mode, adds a penalty or an additional constraint on energy consumption. To reduce the total cost of Idle consumption and therefore the total energy cost, it is preferable to activate a maximum link at the same time (maximum transmission set). This allows also to have the maximum capacity. Conclusion: both models have the same goal. This explains the lack of trade-offs between capacity and energy in Figure 5.

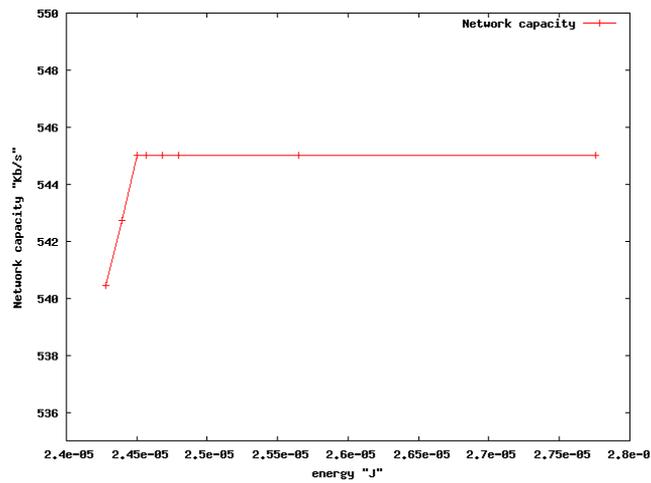


Figure 5: Capacity and energy trade-offs: Idle cost > 0.

6 Conclusion

This paper proposes a preliminary and extensive study of the trade-offs between capacity and energy consumption for wireless mesh network. We have developed a complete multi-objective framework based on linear model and column generation process. Using a binary interference model and a fixed transmit power, we showed that there is no trade-offs where the idle energy consumption is not negligible. For this, we are about to incorporate a more realistic interference model which is based on SINR and adding power control to minimize energy costs and maximize the spatial reuse, which allows to study more the capacity-energy trade-offs. We are also interested in self-configuration where the traffic and the topology can be changed in the time.

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