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Joint Optimization of Routing and Radio Configuration in Fixed Wireless Networks[†]

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Nous étudions la minimisation de la consommation d'énergie des réseaux sans-fil fixes à transmission par liens micro-ondes, par l'optimisation jointe du routage des flux de données et la sélection de la configuration des liens. Nous présentons une formulation mathématique exacte basée sur un multiflot entier de coût minimum avec des fonctions de coût en escalier, rendant le problème très difficile à résoudre. Nous proposons ensuite une fonction linéaire par morceaux convexe, obtenue par interpolation linéaire des points de configuration efficaces en énergie, qui fournit une bonne approximation de la consommation d'énergie sur les liens, et présentons une relaxation qui exploite la convexité des fonctions de coût. Ceci rapporte des limites inférieures sur la consommation d'énergie, et finalement un algorithme heuristique basé sur l'optimum fractionnaire est utilisé pour produire des solutions réalisables. Les résultats attestent du potentiel de notre nouvelle approche.

Keywords: multicommodity flow, radio configuration, power efficiency

1   Introduction

The increasing demand for high-speed data connections has driven a rapid growth of telecommunications technologies. For many reasons, microwave radio links have become a common preference over leased lines to build broadband communication networks [And03]. Despite this fact, network operators are now challenged to reduce operation costs while supporting the enormous growth of bandwidth intensive applications.

In this work, we investigate on minimizing the energy consumption of fixed wireless networks. The network is modeled by a digraph in which the nodes represent radio base stations and the arcs denote radio links. Every link holds a set of power-efficient configurations, each of them associating a capacity with its energy cost. The optimization problem involves deciding both the network's configuration and flows that minimize the total energy consumption, while handling all the traffic requirements simultaneously.

An exact mathematical formulation of the problem is presented. It relies on a minimum cost multicommodity flow (MCMCF) with step increasing cost functions, which is very hard to optimize [Min06]. We then propose a piecewise linear convex function, obtained by linear interpolation of power-efficient configuration points, that provides a good approximation of the energy consumption on the links, and present a relaxation of the previous formulation. This yields lower bounds on the energy consumption, and finally a heuristic algorithm based on the fractional optimum is employed to produce feasible solutions.

2   Link Characterization

The performance of wireless communications is focused on computing signal levels at the receiver, from which we can obtain some implications in terms of channel capacity. Given the allocated bandwidth B and the signal-to-noise ratio (SNR), expressed as a linear power fraction S/N, we can determine an upper bound for the channel capacity C, according to the following Shannon's capacity theorem :

$$C[bits/s] = B[Hz] * \log_2(1 + \frac{S[W]}{N[W]})$$

(a) Theoretical versus practical channel capacities

(b) Step increasing and piecewise linear convex functions
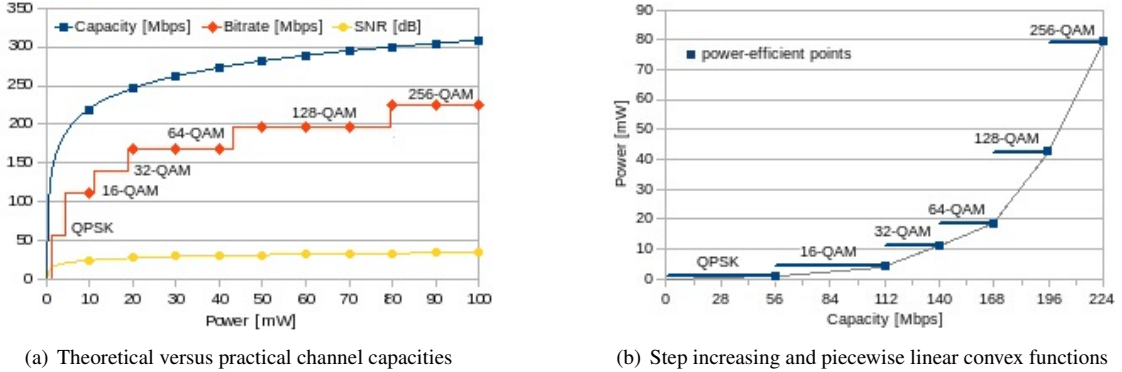
FIG. 1: Capacity and energy cost for QAM modulation schemes

Actually, the degree to which a communication system can approximate this limit depends on receiver noise and modulation. Several features influence the preference for some modulation technique. While focusing on energy consumption, an important factor is the power efficiency : a measure of the received power needed to achieve a specific bit-error-rate (BER) for a given modulation scheme.

Modern communication systems use quadrature amplitude modulation (QAM), which presents high bandwidth efficiency and, when compared to other M-ary modulation techniques, offers a good trade-off between occupied bandwidth and power efficiency. In practice, as the modulation scheme changes to accommodate higher data rates, the SNR requirement increases to preserve the BER performance. Fig. 1(a) shows the theoretical capacity given by Shannon's theorem, the practical bitrate using QAM schemes, and the SNR achieved for a typical radio link scenario in fixed broadband wireless networks.

Under this scenario, a power-efficient configuration can be characterized by a modulation constellation size and a transmission power level. Every radio link holds a set of power-efficient configurations, each of them associating a capacity with its energy cost. Fig. 1(b) illustrates both a discontinuous step increasing and a piecewise linear convex energy cost functions. The latter is obtained by linear interpolation of power-efficient points and provides a good approximation of the energy consumption on the links. Note that, for each modulation scheme, only the most right point of the curve represents a power-efficient configuration.

3 Mathematical Model

In this section, we introduce an exact mathematical formulation to the problem. The energy consumption on each link is given by a step increasing cost function, as shown in Fig. 1(b), and depends on the traffic volume that is supposed to pass through it. This problem can be formally stated as : Given the network's topology as a digraph $G = (V, E)$, where each node $v \in V$ denotes a radio base station and each arc $uv \in E$ represents a radio link from u to v, with $u, v \in V$ and $u \neq v$. Let M_{uv} be the number of power-efficient configurations held by the arc uv, each of them associating a radio link's capacity b_{uv}^m with its energy cost c_{uv}^m, for $m = 1, \ldots, M_{uv}$. We are also given the traffic requirements defined by K oriented pairs of terminals (s_k, t_k), with $s_k, t_k \in V$ and $s_k \neq t_k$, and by the expected demand on them d_k, with $k = 1, \ldots, K$. We want to determine the network's configuration and traffic flow that minimize the total energy expenditure.

Consider the binary decision variable y_{uv}^m which alludes whether the link's configuration m is active for the arc uv, and let x_{uv}^{mk} be the flow through the arc uv under the configuration m with respect to the traffic requirement k. The optimization problem can be formulated as an integer program in which the objective function (1) represents the total energy expenditure that we want to minimize. It counts, for each link, the energy consumption due to the radio operation at a given transmission power level, defined by its configuration. The flow conservation constraints (2), (3), and (4) provide the routes for each demand. By (5), it is assured that, on each link, the available capacity according to its configuration supports the traffic to be routed through it. Finally, the link's configuration choice is determined by (6). It forces a single selection among the possible power-efficient configurations for each link.

$$min \quad \sum_{uv \in E} \sum_{m=1}^{M_{uv}} c_{uv}^m y_{uv}^m \quad (1)$$

$$s.t. \quad \sum_{uv \in E} \sum_{m=1}^{M_{uv}} x_{uv}^{mk} - \sum_{vu \in E} \sum_{m=1}^{M_{vu}} x_{vu}^{mk} = -d_k, \quad (2)$$
$$\forall v \in V, k = 1 \ldots K, v = s_k$$

$$\sum_{uv \in E} \sum_{m=1}^{M_{uv}} x_{uv}^{mk} - \sum_{vu \in E} \sum_{m=1}^{M_{vu}} x_{vu}^{mk} = 0, \quad (3)$$
$$\forall v \in V, k = 1 \ldots K, v \neq s_k, v \neq t_k$$

$$\sum_{uv \in E} \sum_{m=1}^{M_{uv}} x_{uv}^{mk} - \sum_{vu \in E} \sum_{m=1}^{M_{vu}} x_{vu}^{mk} = d_k, \quad (4)$$
$$\forall v \in V, k = 1 \ldots K, v = t_k$$

$$\sum_{k=1}^{K} x_{uv}^{mk} \leq b_{uv}^m y_{uv}^m, \quad (5)$$
$$\forall uv \in E, m = 1 \ldots M_{uv}$$

$$\sum_{m=1}^{M_{uv}} y_{uv}^m \leq 1, \forall uv \in E \quad (6)$$

$$x \in \mathbb{R}^+, y \in \mathbb{B} \quad (7)$$

Unfortunately, this formulation results in large scale integer linear programs. Solution methods for this problem have received little attention in the literature [GM97, AT02]. These studies consider general step increasing functions, where "convexification" may derive poor approximations. In the sequel, we introduce a convexification-based relaxation that takes advantage of the inherent convex shape of the cost functions on the links to obtain lower bounds on the energy consumption and determine the network's configuration.

4   Model Relaxation

In the subsequent formulation, in order to obtain an approximation of the energy consumption on the links, we use piecewise linear convex energy cost functions, as shown in Fig. 1(b). Consider the problem statement, as in the previous section, and the following modifications : now b_{uv}^m represents the incremental of capacity on the arc uv when we move from the configuration $m-1$ to the immediate higher level m, and c_{uv}^m denotes the marginal energy cost into this configuration. As the marginal cost for routing an amount of traffic over higher QAM schemes is always increasing, the configuration for each link can be determined by the variable x of highest level and non-zero value. The problem can be rewritten as :

$$min \quad \sum_{uv \in E} \sum_{m=1}^{M_{uv}} \sum_{k=1}^{K} c_{uv}^m x_{uv}^{mk} \quad (8)$$

$$s.t. \quad \sum_{uv \in E} \sum_{m=1}^{M_{uv}} x_{uv}^{mk} - \sum_{vu \in E} \sum_{m=1}^{M_{vu}} x_{vu}^{mk} = -d_k, \quad (9)$$
$$\forall v \in V, k = 1 \ldots K, v = s_k$$

$$\sum_{uv \in E} \sum_{m=1}^{M_{uv}} x_{uv}^{mk} - \sum_{vu \in E} \sum_{m=1}^{M_{vu}} x_{vu}^{mk} = 0, \quad (10)$$
$$\forall v \in V, k = 1 \ldots K, v \neq s_k, v \neq t_k$$

$$\sum_{uv \in E} \sum_{m=1}^{M_{uv}} x_{uv}^{mk} - \sum_{vu \in E} \sum_{m=1}^{M_{vu}} x_{vu}^{mk} = d_k, \quad (11)$$
$$\forall v \in V, k = 1 \ldots K, v = t_k$$

$$\sum_{k=1}^{K} x_{uv}^{mk} \leq b_{uv}^m, \quad (12)$$
$$\forall uv \in E, m = 1 \ldots M_{uv}$$

$$x \in \mathbb{R}^+ \quad (13)$$

The total energy cost is now given by a continuous linear function (8). The flow conservation constraints (9), (10), and (11) provide, besides the routes, the network's configuration. Finally, by (12), we guarantee that, through every link, the flow over each configuration level does not exceed its capacity.

This formulation gives rise to continuous linear programs that can be easily solved. It yields lower bounds on the energy consumption and, furthermore, quite satisfactory solutions can be obtained by means of simple heuristics based on the fractional optimum. Particularly, we assign for each radio link the lowest-level power-efficient configuration capable of routing the network's flows of the fractional solution.
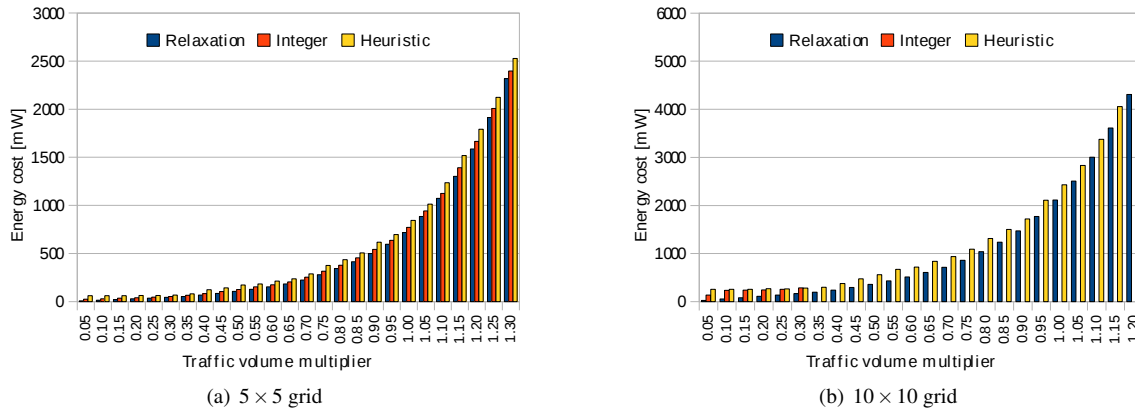
(a) 5×5 grid

(b) 10×10 grid

FIG. 2: Solutions comparison in terms of energy consumption

5 Computational Results

We have used CPLEX to execute the discrete and the continuous program models related to the MCMCF with step increasing and piecewise linear convex energy cost functions, respectively. Numerical values chosen to run the simulations can be found in [CNR08]. The energy cost evolves exponentially as the traffic volume raises (Fig. 2). Overall, the heuristic algorithm performs well compared to the integer solutions and solves instances that are not reachable with the exact approach. After 2 hours of computation for the discrete formulation, feasible solutions were found for all 5×5 grid instances (Fig. 2(a)). However, feasible solutions were found just for the first six 10×10 grid instances (Fig. 2(b)). None of the them was proven to be optimal. Considering the MCMCF with piecewise linear convex cost functions, fractional optimal solutions were found for all instances, and the execution time has never exceeded few seconds. Furthermore, quite good heuristic feasible solutions based on the fractional optimum were generated for all problem instances.

6 Conclusion

In this paper, we presented mathematical formulations for the joint optimization of data routing and radio configuration in fixed broadband wireless networks. In particular, we proposed an approximation of the energy consumption on the links by a piecewise linear convex cost function. A heuristic based on the fractional optimum is used to generate feasible solutions. As future work, we intend to investigate alternative relaxations and heuristics to decrease the gap to the exact solution.

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