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Abstract: In this work, we investigate on minimizing the energy consumption of a wireless backhaul communication network through a joint optimization problem of data routing and radio configuration. The backhaul network is modeled by a digraph in which the nodes represent radio base stations and the arcs denote radio links. According to the scenario under consideration, a power efficient configuration can be characterized by a modulation constellation size and a transmission power level. Every link holds a set of power efficient configurations, each of them associating a capacity with its energy cost. The optimization problem involves deciding the network's configuration and flows which minimize the total energy expenditure, while handling all the traffic requirements simultaneously. An exact mathematical formulation of the problem is presented. It relies on a minimum cost multicommodity flow with stepwise cost functions which is very hard to optimize. We then introduce a linear relaxation of the problem, which exploits the convexity of the energy cost as a function of the throughput on a radio link. This yields lower bounds on the energy consumption, and eventually a heuristic algorithm based on the fractional optimum is presented. Our models are validated through extensive experiments which are reported and discussed. The results of the simulations testify the potentialities behind this novel approach. In particular, our algorithm takes a good advantage of the convexity of the cost function, inducing a quite small integrity gap in practice.

Key-words: Backhaul communication networks, Radio channels, Power efficiency

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Réseaux radio backhaul: minimisation de la consommation d'énergie par la configuration des liens radios

Résumé : Nous étudions la minimisation de la consommation d'énergie des réseaux de communication sans-fil de type backhaul par l'optimisation jointe du routage des données et de la sélection de la configuration des liens. Le réseau backhaul est modélisé par un graphe orienté dont les nœuds représentent les stations radio et les arcs les liens de communication radio. Dans le scénario que nous considérons, une configuration efficace en énergie peut être caractérisée par la taille de la modulation choisie et la puissance de transmission. Chaque lien dispose d'un ensemble de configuration efficaces, chacune associant une capacité à sa consommation en énergie. Le problème d'optimisation à résoudre inclu le choix de la configuration du réseau et le flot minimisant la consommation totale d'énergie, sous la contrainte de satisfaire toutes les demandes de traffic. Nous présentons une formulation mathématique exacte basée sur un multiflot de coût minimum avec une fonction de coût en escalier, rendant le problème très difficile à résoudre. Nous proposons une relaxation linéaire du problème qui exploite la convexité du coût en énergie en fonction de la bande passante du lien radio. Cette relaxation nous fourni des bornes inférieures sur la consommation en énergie. Ceci nous permet égalemet de construire un algorithme heuristique dont les performances sont validées par simulations. Les résultats de simulations attestent du potentiel de notre nouvelle approche. En particulier, notre algorithme heuristic tire profit de la convexité de la fonction de coût pour fournir des solutions à faible écart avec l'optimal.

Mots-clés : Réseaux Backhaul, canaux radio, efficacité énergétique

1 Introduction

The term *backhaul* often refers to transmitting from a remote site to a main site. In telecommunications, the backhaul typically comprises high capacity links to transport traffic between the backbone network and the small subnetworks at the edge of the entire network. Nowadays, microwave radio links are considered as one of the key technologies to build backhaul communication networks, and they are becoming a common preference over leased lines for many reasons, such as economical equipment cost, easy installation, and disaster resiliency [1]. Despite that, wireless network operators are now challenged to reduce operation costs while supporting the rapid growth in bandwidth intensive applications and the very bursty traffic behaviors. In addition, the tremendous rise of energy has yielded a strong social and economical incentive for researchers and manufacturers to investigate on how to reduce energy expenditure of communication systems.

Fostered by the poor behavior of wireless networks when their size increases [2, 3], backhaul and mesh networks have been intensively studied in the recent years with a specific focus on capacity or other QoS parameters and installation costs [4, 5, 6]. Conversely, many researches have focused on minimizing the energy consumption in wireless network, such as minimum energy broadcasting, backbone construction or monitoring in sensor and adhoc networks [7, 8]. In particular, most existing solutions are per-device power optimization while one should focus on a system-wide approach to reach a global energy expenditure minimum. Thus, it is quite consensual that there is still much room for the conceptualization of more sophisticated solutions in this research area.

Furthermore, the optimum configuration choice for wireless backhaul networks is quite different from classical wired networks. Indeed wired channels are stationary and predictable, while wireless links are time-varying in nature (weather conditions can create instantaneously variations in the communication channel) and present a dynamic behavior (for instance, transmission power and modulation format can be adjusted to traffic requirements) [9]. Therefore, wireless communication systems should be flexible to operate efficiently in several different circumstances. As an example, when the traffic demand increases, operators can intensify the transmission power or alternatively change the modulation format to provide additional capacity. In this context, we have to deal with a complex decision for setting the radio link's parameters. This decision consists in determining the optimal system's configuration, taking into account a specific situation and a set of concurrent requirements, such as power consumption, throughput, and latency.

In this work, we are concerned with minimizing energy consumption in wireless backhaul communication networks, focusing on power efficient radio configuration. The backhaul network is modeled by a digraph in which the nodes represent radio base stations (RBS) and the arcs represent radio links. According to the scenario under consideration, a power efficient configuration can be characterized by a modulation constellation size and a transmission power level. 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 which minimize the total energy expenditure, while handling all the traffic requirements simultaneously. It can be seen as a special case of the Minimum Cost Multicommodity Flow (MCMCF) problem, which is largely used for optimal design and dimensioning of telecommunication networks. Nevertheless, to our knowledge, the specific application studied here, i.e. the joint optimization of data routing and radio configuration for minimizing energy consumption, has seldom been addressed in the literature in the role of multicommodity flow problems.

In [10], various special cases of the MCMCF problem are reported, each of them associated with an appropriate choice of link cost function. Generally, the optimization criterion is concerned about the total cost of the equipment to be installed on the various links of the network. When the cost function is considered to be linear, then the MCMCF problem can be formulated as a large scale continuous linear program, and many efficient algorithms are available (see the survey [11]). On the other hand, when considering realistic situations, we have commonly to deal with concave piecewise linear cost functions or step increasing cost functions, giving rise to large scale integer linear programs, much more difficult to solve in practice (see [12] and references therein). These cases usually address the economy of scale phenomenon, where the link's average cost decreases as the installed capacity increases. Precisely, the problem discussed here can be expressed as a MCMCF with discontinuous step increasing cost function but, conversely, the link's average (energy) cost rises as the (channel) capacity is augmented, defining a convex shape of the cost function that we take advantage of in our formulation.

The remainder of the work is organized as follows. In Section 2, we convey more information regarding the radio link characterization and also discuss on power efficiency radio configuration. In Section 3, a minimum cost multicommodity flow mathematical formulation for the application considered here is introduced. Then, in Section 4, we present a linear relaxation which exploits the convexity of the energy cost for tackling this problem. In Section 5, we discuss some computational results we have achieved by experimenting with benchmark problem instances. In Section 6, some final remarks and comments on future work conclude the report.

2 Link Characterization

The analysis of communication systems involves detailed knowledge of the physical channels through which the information is transmitted [13]. There are a lot of electromagnetic phenomena behind the radio wave propagation, such as free space loss, refraction, and reflection. Traditionally, the performance of wireless communications is focused on computing signal levels at the receiver, and it begins with a link power budget, that is, a calculation involving the gain and loss associated with the antennas, transmitters, transmission lines, as well as the signal attenuation due to propagation [1], [9]. The result is an estimation for the signal-to-noise rate (SNR) value, from which we can obtain some implications in terms of channel capacity and bit error rate (BER). Given the allocated channel bandwidth B and the signal-to-noise ratio value S/N, expressed as a linear power fraction, we can determine an upper bound for the channel capacity C, assuming that the bit error rate approaches zero if the data transmission rate is below the channel capacity, according to the following Shannon's capacity theorem [14]:

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

Actually, the degree to which a communication system can approximate this limit depends on receiver noise and modulation technique [15]. The receiver noise is generated by components used to implement the communication system. Other sources of noise may arise externally to the system, such as interference from other users of the channel. With regard to the modulation technique, there are several features which influence the preference of one modulation scheme. Roughly speaking, a desirable modulation scheme provides low BER at low SNR, and occupies a minimum of bandwidth. These requirements are conflicting, and existing modulation schemes do not simultaneously perform all of these requisites. Some modulation schemes perform well in terms of BER performance, while others are better in terms of bandwidth efficiency [9], [16].

Usually, modern communications systems use M-ary digital modulation techniques, and the modulating signal is represented as a time sequence of symbols, where each of them has m finite states and represents n bits of information (with $n = log_2 m$). In practice, when the modulation scheme changes to accommodate higher data rates, the SNR requirement increases to preserve the BER. Since we can increase noise immunity by increasing signal power, there is a trade-off between occupied bandwidth and signal-to-noise performance. While focusing on energy expenditure, an important factor that must be considered is the power efficiency: a measure of the received power needed to achieve a specified bit error rate for a given modulation scheme. In other words, power efficiency represents the ability of a modulation technique to preserve the fidelity of the digital message at low power levels.

Many fixed wireless radio systems use quadrature amplitude modulation (QAM) to support broadband applications. The QAM scheme presents high bandwidth efficiency and, when compared to other M-ary modulation techniques, offers a better trade-off between occupied bandwidth and signal-to-noise performance [17]. A representative graph of SNR versus BER for QAM schemes over a standard digital communication transmission is shown as Fig. 1. Note the roll-off in performance for each type of QAM. By moving to a higher order QAM scheme, it is possible to transmit more bits per symbol. However, if the SNR is to remain the same, as the symbol's constellation is larger, the points must be closer together and are thus more susceptible to noise, resulting in a higher BER.

In what follows, we are concerned with QAM schemes and BER value of 10^{-6}. The premise assumed here is that transmission power and QAM schemes can be configurable to provide the necessary capacity to flow the traffic requirements through the radio channel, while maintaining a given fixed BER. Fig. 2 illustrates the curves of theoretical capacity (given by Shannon's theorem) and practical capacity (using QAM technique) achieved for a typical radio link scenario in backhaul communication networks. Note that, concerning the practical capacity curve, each level is associated with a different QAM scheme. It is also

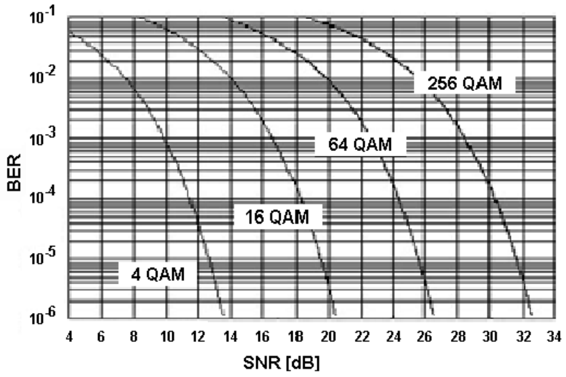

Figure 1: SNR versus BER for different QAM schemes

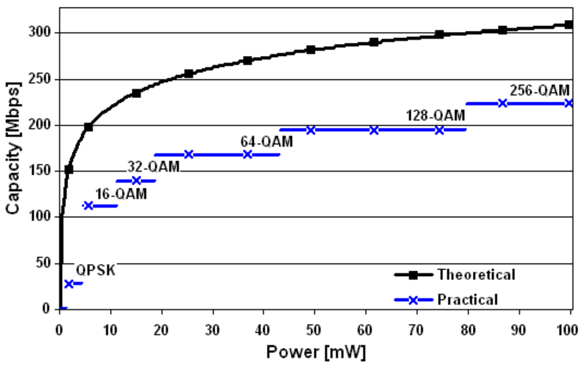

Figure 2: Theoretical versus practical channel capacities

important to remark that, for each capacity level, only the most left point represents a power efficient configuration, i.e. the least energy expensive configuration for a given capacity level.

3 Mathematical Model

Here we revisit the problem of how the network should be configured to minimize energy consumption. Specifically, by configuration, we mean the complete choice of the traffic flows, transmission power and modulation scheme for each radio link. We assume that the radio base stations have a determined range of transmission power levels and a given finite set of modulation schemes. All wireless links are considered to be operated at some required BER.

This problem can be seen as a MCMCF with discontinuous step increasing cost function, and it can be formally stated as: Given the network's topology as a digraph $G = (V, E)$, where each node $v \in V$ denotes a RBS 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 hold by the arc uv, each of them associating a radio link's capacity b^m_{uv} with its energy cost c^m_{uv}, 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 planning and traffic flow which minimize the total energy expenditure. Consider the binary decision variable y^m_{uv} which alludes whether the link's configuration m is active for the arc uv, and let x^{mk}_{uv} be the flow through the arc uv under the configuration m with respect to the traffic requirement k. Finally, the problem can be formulated as:

$$min \quad \sum_{uv\in E}\sum_{m=1}^{M_{uv}} c^m_{uv} y^m_{uv} \tag{1}$$

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

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

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

$$\sum_{k=1}^{K} x^{mk}_{uv} \leq b^m_{uv} y^m_{uv}, \quad \forall uv \in E, m = 1 \ldots M_{uv} \tag{5}$$

$$\sum_{m=1}^{M_{uv}} y^m_{uv} \leq 1, \forall uv \in E \tag{6}$$

$$x \in \mathbb{R}^+, y \in \mathbb{B} \tag{7}$$

In this formulation, the objective function (1) represents the total energy expenditure that we want to minimize. The flow conservation is expressed by (2), (3), and (4). By (5), we guarantee that, for each link, the capacity associated with its current configuration is capable of flowing all the traffic routed through it. Finally, the link configuration choice for each link is obtained by (6). Unfortunately, as mentioned before, this formulation results in

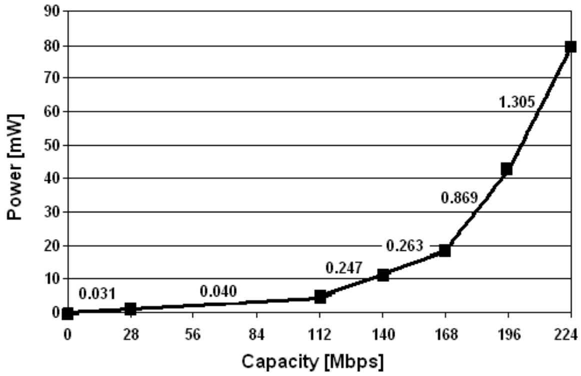

Figure 3: Approximative convex piecewise energy cost function

large scale integer linear programs, which are very difficult to solve in practice. In addition, solution methods for this problem have received very little attention in the literature. In the sequel, we introduce a linear relaxation program model to tackle this problem.

4 Model Relaxation

In the subsequent formulation, we give a linear approximation model where the overall energy consumption is given by the sum of the link's energy cost functions. For every link, this function presents a piecewise linear form, as illustrated in Fig. 3, and depends on the amount of flow routed through it. All interval endpoints denote power efficient configurations for a given radio link. The decimal numbers over each interval give an approximation of the energy cost per unit of capacity on this interval, taking into account a real world scenario. Observe that the link's energy cost function is convex, monotonically increasing, and piecewise linear. Therefore, the marginal energy cost for routing an amount of traffic over higher QAM schemes is always increasing.

In view of all these considerations, the problem can be rewritten as a MCMCF with linear cost function. Consider the problem statement, as in the previous section, with these following modifications: now b represents the incremental of capacity when we move from a specified QAM scheme to the immediate higher one, and c denotes the marginal energy cost for a particular capacity interval. Since we do not consider anymore the binary decision variable y, for each link, the active configuration is implicitly determined by the variable x of highest configuration level and non-zero value. The problem can be then formulated as:

$$
\begin{aligned}
min \quad & \sum_{uv \in E} \sum_{m=1}^{M_{uv}} \sum_{k=1}^{K} c_{uv}^{m} x_{uv}^{mk} && (8) \\
s.t. \quad & \sum_{uv \in E} \sum_{m=1}^{M_{uv}} x_{uv}^{mk} - \sum_{vu \in E} \sum_{m=1}^{M_{vu}} x_{vu}^{mk} = -d_k, && (9) \\
& \forall v \in V, k = 1 \dots K, v = s_k \\
& \sum_{uv \in E} \sum_{m=1}^{M_{uv}} x_{uv}^{mk} - \sum_{vu \in E} \sum_{m=1}^{M_{vu}} x_{vu}^{mk} = 0, && (10) \\
& \forall v \in V, k = 1 \dots K, v \neq s_k, v \neq t_k \\
& \sum_{uv \in E} \sum_{m=1}^{M_{uv}} x_{uv}^{mk} - \sum_{vu \in E} \sum_{m=1}^{M_{vu}} x_{vu}^{mk} = d_k, && (11) \\
& \forall v \in V, k = 1 \dots K, v = t_k \\
& \sum_{k=1}^{K} x_{uv}^{mk} \leq b_{uv}^{m}, && (12) \\
& \forall uv \in E, m = 1 \dots M_{uv} \\
& x \in \mathbb{R}^{+} && (13)
\end{aligned}
$$

This formulation exploits the convexity of the energy cost over the throughput on the radio link. By this means, flows over a higher configuration level will take place only in the case where lower configuration levels' capacity is not sufficient to accommodate them. The total energy cost is now represented by a linear function (8). The flow conservation constraints (9), (10), and (11) remain as in the previous model. Finally, by (12), we guarantee that, through every link, the flow over each configuration level do not exceed its capacity.

This model can be solved by various linear programming solvers, even if we have to deal with very large problem instances. Despite the fact that the resulting optimal solution of the associated linear program is not a practical one, it yields lower bounds on the energy consumption. Furthermore, even if we make use of basic heuristics based on the fractional optimum, satisfactory viable solutions can easily be obtained. Particularly, in this work, we consider a heuristic algorithm that selects for each radio link the lowest power efficient configuration able to route all the fractional flows of that link.

5 Computational Results

In a manner as to testify the potentialities behind the novel approach, we have performed computational experiments on standard benchmark grid network instances [18]. To compute the data related to power efficient configurations and energy cost functions, since we are dealing with wireless backhaul communication networks, the subsequent scenario was considered. Each Radio Base Station makes use of directional antennas and transceivers devices with identical characteristics, and all radio links are operated in the same frequency and bandwidth. We assume here the free space path loss attenuation model and do not consider interference, but receiver noise. The following parameters values are assumed:

- Channel Bandwidth: 28 MHz;
- Operated Frequency: 13 GHz;
- Antenna Gain: 30 dBi;
- Receiver Sensitivity: -90 dBm;
- Distance: 1000 m.

We have performed experiments on a 5×5 and on a 10×10 grid networks using the traffic matrix given in [18]. In order to observe the evolution of the energy cost as a function of the traffic amount, we have multiplied the traffic matrix by a factor λ in the range 0.05...1.3. The integer and linear program models were solved using CPLEX, however the integer result is the best feasible solution obtained after 2 hours of computation (none of them was proven optimal, and only two of them are feasible for the 10×10 grid).

Due to the shape of the energy cost function of Fig. 3, the relaxed model aims to balance the usage of the links, and so the traffic will be spread among several links of the network. Therefore, when rounding up the capacity of the links in the heuristic algorithm, many links may use a higher configuration to carry a small extra amount of traffic that could have been routed through other links. On the opposite, and due to the stepwise cost function, the exact model aims to improve the usage of each link.

For example, in a network with 4 nodes A, B, C, D, 4 links AB, AC, CD, DB, and a traffic matrix with 4 demands of 10 Mbps each, AB, AC, CD, DB. The relaxed model will route each request on a single link for an overall cost of 1.24 mW. Thus the heuristic will round up the capacity of all links to 28 Mbps for an overall cost of 3.5 mW, but the exact model will route demand AB through links AC, CD, DB thus avoiding to use link AB, and the overall cost will be 2.63 mW.

This explains why the gap is large in Fig. 5 and 7 when λ is small since many links are under-used to transport a small amount of traffic. This also explains why the gap increases in Fig. 5 when λ increases from 0.15 to 0.20 or from 0.30 to 0.35, that is when configurations of higher capacity start to be used. As expected, results reported in Fig. 4 and 6 show that the energy cost increases exponentially with the traffic.

Overall, our computational results show that the heuristic algorithm based on the relaxed model performs well compared to the exact model. Furthermore, the computation time of the heuristic algorithm is very small compared to the exact model and the heuristic allows to solve instances that are not reachable with the exact model. This can be seen in Fig. 7 where valid solutions have been found with the exact model only for $\lambda = 0.05$ and 0.10.

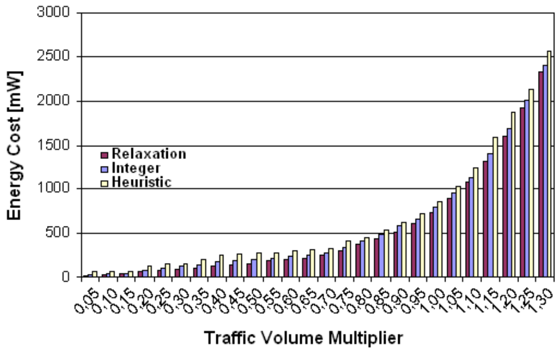

Figure 4: Grid 5 × 5 - Solutions comparison in terms of energy consumption

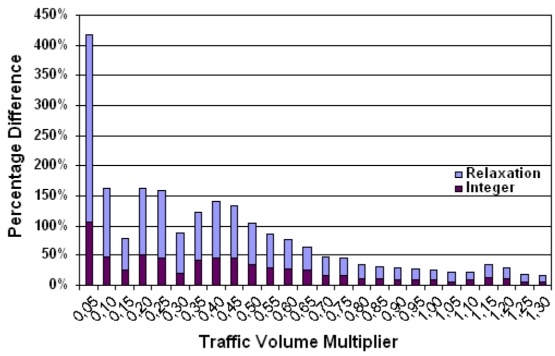

Figure 5: Grid 5 × 5 - Heuristic compared to linear and exact solutions

6 Conclusion

In this paper, we presented two mathematical formulation for the joint optimization of the routing and configuration in wireless backhaul networks. In particular, we proposed a novel approach to handle the energy cost function as a piecewise linear function. Based on the linear relaxation model, we build a heuristic algorithm that performs well according to computational experiments.

In future work, we will introduce other parameters in the optimization process such as delay, survivability and traffic variations. We will also investigate other heuristic algorithms to decrease the gap with the integer solution.

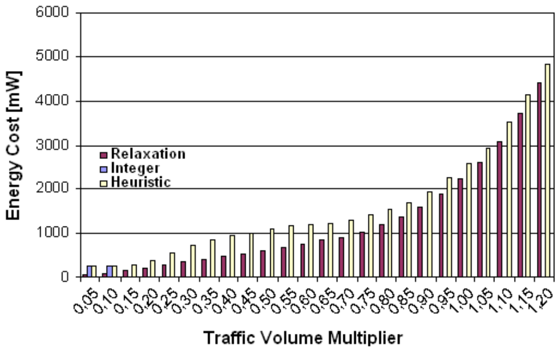

Figure 6: Grid 10 × 10 - Solutions comparison in terms of energy consumption

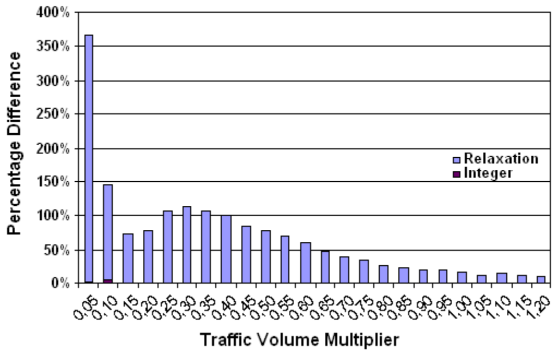

Figure 7: Grid 10 × 10 - Heuristic compared to linear and exact solutions

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