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Optimization methods applied to nonlinear signal interference models

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ABSTRACT: In wireless mesh networks, it is important to establish the transmission capacity of the links, taking into account the presence of noise that interferes with the transmission and consequently degrades the signal sent from one device to another. This signal degradation is calculated from interference models, such as SNR (Signal-to-Noise Ratio), SIR (Signal-to-Interference Ratio) and SINR (Signal-to-Interference-plus-Noise Ratio). In these models, the link capacity is calculated according to a decreasing of power levels, depending on the noise or interference present, which needs to be adjusted to acceptable levels, in order to avoid committing the signal emission besides not causing health damage to people close to the device. Different models can be used to estimate the noise present in an environment. In wireless transmission, however, it is possible to calculate the noise by means of nonlinear equations, which are able to estimate the interference levels present in the network links. From these elements, it is possible to maximize the capacity of the network links, using models of nonlinear programming. As these models are difficult to be solved analytically, this work compares the results of different nonlinear programming models, based on the main interference models, with the results obtained by a classical approach for solving nonlinear models: The simulated annealing metaheuristic. In this paper, it will analyze the behavior of the heuristic algorithm, regarding the quality of the solution obtained and the processing time, as the network size increases.

1 INTRODUCTION

Nowadays, wireless networks are a disseminated technology mainly because of popularization of wireless devices, such as smartphones, tablets, laptops, etc. These devices receive the signal from routers or towers that send data packets through signals in a given bandwidth.

However, in a wireless transmission, the signal not received with desired quality implies in affecting the quality of service. One of the main problems found in wireless transmission is the presence of elements that cause degradation in the transmission signal. Many elements can interfere in the quality of wireless transmission, such as wind, rain, trees, animals, buildings and other types of elements present in wireless environment. These elements can refract or block the signal, holding the received signal to some users. Figure 1 shows environment elements who may degrade wireless signal and is usually found on a daily basis.

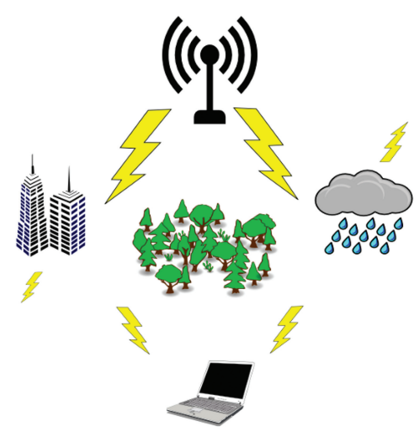

Figure 1. Example about power decreasing in environment.

This figure exemplifies the difficulty for the signal to travel to the client device. Consequently, the signal received by client is degraded during the hop, with the presence of noise that compromises the quality of service offered. Other element that may compromise the wireless signal is the presence of other type of signals where, according to frequency used, can interfere directly in transmission.

Some models can estimate the degraded signal in wireless link, in order to quantify power levels that each router can use to transmit data packets to clients, according to link capacity and quality of service (QoS) parameters. In order to estimate power levels, some interference models are adopted, according to signal ratio used. The main models used are the *Signal-to-Noise-Ratio* (SNR), the *Signal-to-Interference-Ratio* (SIR) and the *Signal-to-Interference-plus-Noise-Ratio* (SINR). All of these models reflect directly to link capacity values and their respective equations are non-linear, due to use of Shannon capacity equation. The objective is, in these cases, maximize the network capacity. The objective function is composed by Shannon equation (Johansson & Xiao 2006), implying a Non-Linear Programming Model.

Non-Linear Programming models are not trivial to solve by *solvers* (softwares capable to find solutions for Mathematical Programming models in low computational time) and, in this case, one has to employ metaheuristics to obtain results more accurately. One of metaheuristics used to Non-Linear Programming model is the Simulated Annealing algorithm, due to effectiveness, easy to program and to apply non-linear equations, either in objective function or in constraints of the model.

This paper proposes Non-linear Programming interference models (NonPrIM), with an objective to maximize power levels in a wireless network, subject to power constraints. Section 2 lists the main works related with interference models, their characteristics and methods to find solution for this class of problems. The proposed model is described in Section 3, while the Simulated Annealing applied to model proposed is described in Section 4. Section 5 shows the computational results and the section 6 shows the paper conclusions and proposes future works.

2 INTERFERENCE MODELS

In wireless networks, link capacity is a research area of interest that received more efforts mainly due to the increasing of this technology and, consequently, the increase number of devices that request many Internet services daily around the world. Some papers, such as Gupta & Kumar (2000), Maheshwari, Jain, & Das (2008), Weber & Andrews (2012), highlight the importance of estimating the link capacity over a wireless network and its effects on environment to transmission quality to users due to interference suffered by the link.

As mentioned earlier, interference models are important to estimate witch power levels must be used for data traffic without affecting neither quality of service nor users health. In this case, energy consumption is not the focus, due to routers in the most used wireless networks (e. g. IEEE 802.11) are not a problem (Brar, Blough, & Santi 2006). On the other hand, power levels are related directly with energy consumption when the routers are composed by sensors (Moscibroda 2007).

In cross-layer design, an ideal scenario modelled by MAC layer is transmitting data packets to a destination without any interference (Maheshwari, Jain, & Das 2008). However, in environment, many elements (see Figure 1 in Section 1) cause interference in wireless signal and degrade the power transmission, requiring more effort by router to transmit the signal with quality. In cross-layer optimization, the interference model evaluation is important to estimate which power levels must be used to transmit data packets to clients, in order to power consume can not be high. From the point of view of the physical (PHY) layer, a transmission is successful if and only if interference level is less than a threshold so that the transmitted signal can be decoded with an acceptable bit error probability (Shi, Hou, Liu, & Kompella 2009).

The impact of interference models in network layer is shown in Yuan, Li, Yu, & Li (2006), where a cross-layer optimization model is decomposed in two modules, where one contains link interference model constraints in PHY layer, required for establishing the best ways to transmit packets, in this case, specific to wireless mesh networks (WMNs). ***The results obtained in PHY layer is used to solve the module based on network layer for obtaining data flow on links between routers.***

Shabdanov, Mitran, & Rosenberg (2012) propose a cross-layer optimization focused in advanced techniques on PHY layer that allow verifying the network behavior in cases where different types of interference model are used, according to transmission mode. However, they focused mainly in transmission mode, while this paper focuses directly in interference models.

In this paper, three of main interference models to estimate link capacity is used in different wireless networks. One of these is the *Signal-to-Noise-Ratio* (SNR), that consists in ratio between the signal power sent (denoted by P_j) and the noise found in environment (denoted by P_{noise}) (Laneman, Tse, & Wornell 2004). Thus, the SNR formula is basically denoted by:

$$SNR_j = \frac{P_j}{P_{noise}} \tag{1}$$

Other interference metric is the *Signal-to-Interference-Ratio* (SIR) used directly to verify the amount of signal interference suffered compared with a signal transmitted on a link. In Haidar, Ghimire, Al-Rizzo, Akl, & Chan (2008), for example, SIR is used to find the maximum value for throughput in a channel assignment problem. Thus, SIR is denoted by the ratio between the signal sent and the interference value $P_{interference}$ as follows:

$$SIR_j = \frac{P_j}{P_{interference}} \tag{2}$$

However, in a realistic scenario, there is the presence of interference caused by different signal conflict (measured by SIR) and the environment noise (measured by SNR). Specially, in wireless networks, it is usual to adopt the presence of both elements in signal degradation. In this case, *Signal-to-Interference-plus-Noise-Ratio* (SINR) is used to establish the power decreasing from the combination of SIR and SNR characteristics in order to relate the signal with combination between both interference and noise occurred on a link. Hence, SINR can be obtained from the ratio between the signal sent and the sum of noise coefficient (P_{noise}) and the interference signal ($P_{interference}$), denoted by:

$$SINR_j = \frac{P_j}{P_{noise} + P_{interference}} \tag{3}$$

SINR is widely used in cross-layer optimization models to estimate link capacity in order to determine data flow between two network nodes. Some papers in this area aim to maximize the throughput, where power constraints take into account equations that estimate SINR, as seen in Johansson & Xiao (2006). In Tang, Xue, & Zhang (2009), Le & Hossain (2008), Liao & Elhakeem (2012) and Bansal & Trivedi (2014), interference models are calculated also in WMNs to measure SINR between two mesh routers.

To calculate link capacity based on interference models, each link can be viewed as a single-user Gaussian channel, being associated with the link capacity. Let j an index to a link and C_j its respective link capacity. Hence, the link capacity can be obtained from Shannon equation (Johansson & Xiao 2006), denoted by:

$$C_j = W \log_2 \left(1 + \frac{P_j}{P_{model}}\right) \tag{4}$$

where W is the system bandwidth and P_{model} can vary according to adopted interference model. Note that Shannon equation is non-linear, that implies in being difficult to be implemented in this type of equation within a optimization model.

For this class, metaheuristics are used to find a good solution in a reduced computational time compared to exact models (Szu & Hartley 1987), (Roeva & Trenkova 2012). One of the most used metaheuristics is the Simulated Annealing algorithm (Lorena & Senne 2004), that can be used in Nonlinear Programming (NP) models, as seen in Sousa, Morais, Vale, Faria, & Soares (2012). So, this paper brings the idea of applying the Simulated Annealing in our Nonlinear Programming Interference Models, and will be shown in the next section.

3 NONLINEAR PROGRAMMING FOR INTERFERENCE MODELS (NONPRIM)

As seen in Section 2, interference models are used to estimate the link capacity over a wireless network, in order to measure what power level must be set for each network device. From three main interference models (SNR, SIR and SINR), these proposed models are called as Nonlinear Programming for Interference Models (NonPrIM).

Table 1. Parameters used in NonPrIM.

Parameter	Description
β	QoS threshold
G_{jj}	Power gain on link j
G_{ji}	Power interference from link i to link j
ν	Noise coefficient j
P_n	Maximum power of a AP $n \in \mathcal{N}$

The following elements are present in NonPrIM. Let $\mathcal{L} = \{1, \ldots, L\}$ be the set of links in a wireless network and $\mathcal{N} = \{1, \ldots, N\}$ the set of network devices. From these sets, two groups of variables are considered to the problem. Let p_j be the power transmission used to transmit data packets in a link $j = (n_j^s, n_j^r) \in \mathcal{L}$, where n_j^s is the sender network device and n_j^r is the receiver device for respective link j. From results obtained to power transmission, it is obtained the link capacity for every link $j \in \mathcal{L}$, denoted by κ_j.

After establishing the variables, the main objective of NonPrIM is maximize the link capacity of a network, in order to optimize also power transmission. Let κ_j be the capacity of a link $j \in \mathcal{L}$. Hence, the objective function is determined by the sum of all link capacities, given by:

$$\max \sum_{j=1}^{L} \kappa_j \tag{5}$$

On the other hand, some parameters are determined previously, in order to establish the network configurations. From these parameters, NonPrIM finds the best solution, according to constraints that use these values. Table 1 indicates the parameters and their respective functionalities, that will be explained in the section.

Constraints can be grouped into two types. One of these types is the limitation of power transmission from a device, denoted by inequation

$$\sum_{j \in \mathcal{L}_n^+} p_j \leq P_n \qquad \forall n \in \mathcal{N} \tag{6}$$

where all power transmission from links whose sender is the device n must be less than the power limitation, denoted by P_n. Other constraints are classified according to interference model adopted for the wireless network.

3.1 *SNR constraints*

In case the network has only noise on environment, the use of SNR is applied in order to establish which power levels are necessary for a good succeeded transmission. Thus, the SNR constrains are:

$$SNR_j = \frac{G_{jj} p_j}{\nu} \qquad \forall j \in \mathcal{L} \tag{7}$$

$$SNR_j \geq \beta \qquad \forall j \in \mathcal{L} \tag{8}$$

$$\kappa_j = \log_2 (1 + SNR_j) \qquad \forall j \in \mathcal{L} \tag{9}$$

In equation (7), the SNR formula is based on equation (1), where the SNR on each link is denoted by the ratio between the power gain of a link j and the noise coefficient. Results obtained from this equation have two constraints. Constraint (14) shows that the SNR of the link j must be greater than a QoS threshold, denoted by β. In constraint (15), the Shannon equation is applied to determine the link capacity from a logarithmic function based on SNR obtained.

3.2 *SIR constraints*

The SIR model is applied for environments where the presence of interference caused by other signals is detected. This interference may degrade signal and damage it. In this case, the link capacity can be estimated from SIR equations by constraints:

$$SIR_j = \frac{G_{jj}p_j}{\sum_{\iota \neq j} G_{j\iota}p_j} \qquad \forall j \in \mathcal{L} \tag{10}$$

$$SIR_j \geq \beta \qquad \forall j \in \mathcal{L} \tag{11}$$

$$\kappa_j = \log_2(1 + SIR_j) \qquad \forall j \in \mathcal{L} \tag{12}$$

Constraint (10) represents the SIR calculated in equation (2), where the link power is divided by the sum of interference levels from other links. The QoS levels desired for SIR model is represented by constraint (11). In nonlinear equation (12), the link capacity is estimated in function of SIR obtained in previous constraints.

3.3 *SINR constraints*

SINR model is the most used in wireless networks due to the presence of interference and noise in each link. This model combines the main characteristics of SIR and SNR models. This model can be represented in NonPrIM from constraints:

$$SINR_j = \frac{G_{jj}p_j}{\nu + \sum_{\iota \neq j} G_{j\iota}p_j} \qquad \forall j \in \mathcal{L} \tag{13}$$

$$SINR_j \geq \beta \qquad \forall j \in \mathcal{L} \tag{14}$$

$$\kappa_j = \log_2(1 + SINR_j) \qquad \forall j \in \mathcal{L} \tag{15}$$

Equation (3) presented in Section 2 is denoted in the NonPrIM by constraint (13), where SINR formula is used in other two constraints: in inequation (14), the SINR must be greater than QoS threshold, denoted by β, while constraint (15) calculates the link capacity using Shannon equation in function of SINR obtained.

Both variable classes (p_j and κ_j) can not be negative, for each link $j \in \mathcal{L}$. NonPrIM may be solved using one of three types of model interference, once each model represents a specified case according to environment where wireless network will be traffic data. To solve NonPrIM, is used a metaheuristic applied to Nonlinear Programming model – Simulated Annealing algorithm.

Table 2. Elements used in SA-NonPrIM.

Element	Description
p_0	Initial solution
T_0	Initial temperature
SA_{max}	Maximum of iterations of SA
α	Cooling rate
ϵ	Tolerated error rate

4 SIMULATED ANNEALING APPLIED TO NonPrIM

Due to nonlinearity of NonPrIM, in the Shannon equations (see constraints (9), (12) and (15)), one effective alternative to find a good solution for this type of problem is to consider metaheuristics. However, not all the metaheuristics may be used for Nonlinear Programming models, because some are specified to problems focused in Combinatorial Optimization for Integer Programming models. Hence, one of metaheuristics most used for this case is Simulated Annealing (SA) algorithm.

For the NonPrIM, SA is adapt specially to this problem, in order to find a good solution efficiently. The advantage of Simulated Annealing is the strategy of re-increasing of temperature, here denoted by T, to find other solutions that can be better than the local optimal. In this algorithm, the main elements used are listed in Table 2.

Using the elements presented in the Table 2, the Simulated Annealing algorithm applied in NonPrIM is described in Algorithm 1.

Algorithm 1: Simulated Annealing applied to NonPrIM

```
Input: (p_0, T_0, SA_max, α)
p ← p_0;
p_opt ← p;
iT ← 0;
T ← T_0;
while T > ϵ do
    while iT < SA_max do
        iT ← iT + 1;
        p_next ← Neighbour(p);
        Δf ← f(p_next) − f(p);
        if Δf < 0 then
            p ← p_next;
            if f(p) > f(p_opt) then
                p_opt ← p;
        else
            rnd is random value ∈ [0, 1];
            if rnd < e^(−Δ/T) then
                p ← p_next;
    T ← α × T;
    iT ← 0;
f(p_opt) = Σ κ(p_opt)
Output: f(p_opt)
```

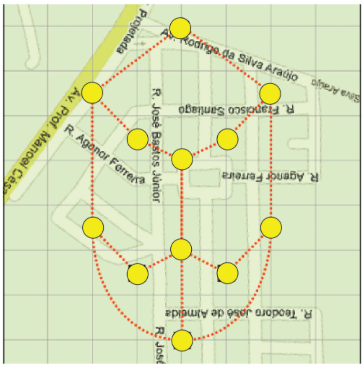

Figure 2. A hypothetical wireless network.

Table 3. Results obtained from default configuration.

Average value per model	SNR	SIR	SINR
Link capacity (Mb/s)	39.56	70.12	1.80
Power level (mW)	50.00	47.40	47.34

In this algorithm, while the temperature does not decrease until the tolerated limit, a new solution from neighbourhood is choose and compared. If the solution is not optimal, a new search is done, until the cooling has been completed and an optimal solution p_{opt} is found. The neighbourhood search is done inside of threshold temperature, in order to other solutions be explored and, thus, avoid a local optimal solution be considered as global in the search interval. Once obtained values to p_{opt}, the optimal values for each link capacity κ_j are obtained and, consequently, the value closed to global optimal value for objective function is found.

5 NUMERICAL RESULTS

The Simulated Annealing for NonPrIM was applied on a hypothetical network illustrated in Figure 2. The values for channel gain are defined by the formula $G_{ij} = 1/d_{ij}^{\eta}$, where $\eta = 3$ is the path loss exponent and d_{ij} is the Euclidean distance between the sender router i and the receiver node j. As default configuration, the maximum power used by routers may be $P_n = 100$W, the noise coefficient $\nu = -100$ dBm and QoS threshold $\beta = 10$ dB.

For initial values used in the Simulate Annealing algorithm, the cooling rate $\alpha = 0.9$, where α must be close than 1 for better results. The initial temperature $T_0 = 1000$ and the initial solution p_0 is chosen randomly with values between 0 and 0.2 for each power link.

Given values for default configuration, the results obtained by algorithm are presented in Table 3. In this configuration, the three models (SNR, SIR and SINR) are compared to explore the behavior in each case.

Table 4. Link capacity when maximum power is modified.

P_n	SNR	SIR	SINR
50	19.52	44.71	0.98
100	39.56	70.12	1.80
150	58.18	86.79	2.48
200	77.08	98.60	3.10
300	113.64	114.02	4.20

From the results illustrated in the previous table, the link capacity of the network in SINR model is less than other two models. This occurs because the presence of noise and interference simultaneously.

In other hand, the average power level in every models is approximated, where each link is in 47 and 50 mW, in acceptable threshold for all scenarios. Thus, in results, the both presence of noise and interference can degrade the signal sent by a router, where this scenario is very used in wireless networks that operates in IEEE 802.11 protocols – one of the most used and more popularized between domestic users.

In other scenarios for used network, the maximum power sent by each network router is modified, in order to verify the behavior of link capacity when this parameter is modified. The Table 4.

Note that, when the maximum power link is increased, the link capacity is increase slowly, mainly in case of SIR model, when $P_n = 300$ mW, the link capacity is almost equal to link capacity to SNR model, while $P_n = 50$ mW, the link capacity in SIR model is almost two times greater than obtained in SNR model. However, the values obtained in SINR model is much lower compared to other models.

6 CONCLUSIONS

This paper presented an example of Nonlinear Programming model specific to measure how to modify a link capacity under a wireless environment. NonPrIM established a comparison between the three main decreasing signal models: SNR, SIR and SINR, used in different environment scenarios. As the model is nonlinear, a metaheuristic was used to find a good solution, in this case, the Simulated Annealing algorithm due to easily in develop the code and because the efficient computational processing.

As future works, NonPrIM will be part of a cross-layer optimization model, as a component to find a solution to link capacity combined with data flow and channel assignment, considering two components of a Mixed Integer Linear Problem. Furthermore, NonPrIM allows the use of other metaheuristics, in order to compare the efficiency between Simulated Annealing with other classic metaheuristics, such as VNS.

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