CROSS-LAYER OPTIMIZATION APPLIED TO OBTAIN TIME METRIC SPECIFIED TO WIRELESS MESH NETWORKS

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ABSTRACT

Time metrics are extremely important to evaluate performance of multimedia transmissions on wireless net-works, mainly in wireless mesh networks (WMNs), whose characteristic is to provide Internet access to remote devices. An example of such a metric is WCETT (Weighted Cumulative Expected Transmission Time), in which each time of transmission per hop is a weighted average based on proactive and reactive conditions. This paper presents a combination of solutions to minimize WCETT in a given model subject to constraints in some of the network layers: Mixed Integer Linear Programming and use of a heuristic. The heuristic is based on decomposing in subproblems represented by each layer used in the model.

Keywords: Wireless mesh networks, ETT, WCETT, Cross-layer optimization.

1. Introduction

Wireless Mesh Networks (WMNs) [1] are employed in areas where extensive coverage with low cost is required. Domestic users have been adopting such networks to use Internet multimedia services. The main characteristic of WMN is the multihop technology, capable to relay data packets over devices known as Access Points, or APs. APs can be classified into two groups: gateways and routers. Gateways are APs connected directly to an external network (e. g., a wired network) and routers are relays to communicate with other APs providing access to Internet for clients with wireless devices, such as tablets, mobile phones and laptops. Figure 1 shows an example of WMN.

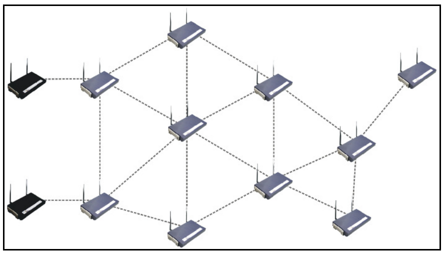

Figure 1 – A Wireless Mesh Network where black devices are gateways and gray devices are routers.

Multimedia transmissions have become quite common nowadays. It becomes a great challenge to ensure a good configuration of communication between layers of a WMN to satisfy high quality levels, so that effects of delay in data transmission are not perceived by the users. This problem becomes much more complex when designing cross-layer aspects within the network. In this design, the performance of the layers must be analyzed based on protocols located in each layer responsible for intercommunication between them. This means, that, some metrics have to be extracted to evaluate whether the network satisfies the users expectations [2]. Usually, the main metric extracted is the throughput [3], [4], [5], [6]. Throughput alone may not be enough to properly evaluate network's performance with respect to delay. Each hop must also be considered.

In order to evaluate each hop, some specific metrics for WMNs are adopted such as ETX (Expected Transmission Count) and ETT (Expected Transmission Time) [7]. In terms of routing, WMN must be evaluated in terms of the path in which data packets can traverse up to the client that requested them. Another metric, Weighted Cumulative Expected Transmission Time (WCETT), calculates ETT assigning weights, i. e., accumulated on the path traversed by the packets. One advantage is that this metric aggregates characteristics located in routing protocols, such as OLSR [8]. The advantage lies in the fact that the route is already determined at each hop, and, exactly at each hop, metrics can be extracted.

This paper proposes an optimization model that minimizes the WCETT of a WMN, considering the fixed link capacity, using a Mixed Integer Linear Programming (MILP) model, subject to conditions of relationship between layers, grouped by subproblems. In turn, these subproblems are decomposed so that a heuristic is employed to solve them separately. The solution is based on an iterative process that should converge to a specified time metric per hop. The results are represented by binary and real values based on combinations between channels and sessions per each link according to metrics that can dictate a good performance of the network. This paper is organized as follows: Section 2 presents the mathematical formulation (MILP) proposed for this problem, as well as the heuristic to minimize WCETT. Numerical results are presented in Section 3. Section 4 presents some conclusions and proposes future works.

2. The Proposed Model

To formulate the mathematical model, let a WMN be denoted by a graph (**N**, **L**), where **N** = {1, ..., N} represents the set of APs (routers and gateways) and **L** = **N** × **N** = {1, ..., ℓ} the set of links. Let **C** = {1, ..., C} be the set of channels to be used by the links. The use of several channels is important to avoid interference between different types of data that travel in the same frequency [9]. Consider also the set of data sessions **S** = {1, ..., S}, where each session is denoted by a 3-tuple (n_o, n_d, λ_k), where n_o and n_d are, respectively, the sender AP (that originated the message) and receiver AP (that is the destination to which message should be received) and λ_k ($k \in$ **S**) is the data flow size.

The proposed model is focused in minimizing WCETT, taking into account all data sessions in the WMN, their respective links and channels, composing the set of decision variables and their respective parameters. Table 1 shows the variables used in the problem, while Table 2 lists the associated parameters of the model.

Table 1 – MILP model variables

Variable	Type	Description
f_{ij}^k	Non-negative real	Data flow that travels on each link $j \in$ **L**, using the channel $i \in$ **C** for session $k \in$ **S**
x^k_{ij}	Binary	Channel conditions: 1, if the channel i will be used for link j on session k; 0, otherwise
τ^k_{ij}	Non-negative real	ETT of each link $j \in$ **L** that travels on channel $i \in$ **C** in the session $k \in$ **S**
d_i	Non-negative real	Maximum value for ETT to be found between channels, where $i \in$ **C**

Table 2 – MILP model parameters

Parameter	Description
κ_j	Link capacity, defined from bandwidth constraints
χ	ETX, given by a probabilistic parameter [7]
ℓ_n	Maximum amount of links connected in an AP $n \in$ **N**
T	Maximum time for transmission per hop

Based on the variables and values presented in the tables above, MILP formulation to find a solution to the model follows:

$$\min \sum_{i=1}^{c} \left[(1-\gamma) \sum_{j=1}^{\ell} \sum_{k=1}^{s} \tau_{ij}^k + \gamma d_i \right] \tag{1}$$

Subject to:

$$d_i \geq \sum_{j=1}^{\ell} \sum_{k=1}^{s} \tau_{ij}^k \qquad \forall i \in \mathbf{C} \tag{2}$$

$$\sum_{p \in L_{n+}}^{\ell} \sum_{i=1}^{c} f_{ip}^k - \sum_{q \in L_{n-}}^{\ell} \sum_{i=1}^{c} f_{iq}^k = 0 \qquad \forall k \in \mathbf{S}, n \in \mathbf{N} - \{n_s, n_r\} \tag{3}$$

$$\sum_{p \in L_{n+}} \sum_{i=1}^{c} f_{ip}^k - \sum_{q \in L_{n-}} \sum_{i=1}^{c} f_{iq}^k = \lambda_k \qquad \forall k \in \mathbf{S}, n \in \{n_s\} \tag{4}$$

$$\sum_{p \in L_{n+}} \sum_{i=1}^{c} f_{ip}^k - \sum_{q \in L_{n-}} \sum_{i=1}^{c} f_{iq}^k = -\lambda_k \qquad \forall k \in \mathbf{S}, n \in \{n_r\} \tag{5}$$

$$\sum_{i=1}^{c} x_{ij}^k \leq 1 \qquad \forall j \in \mathbf{L}, k \in \mathbf{S} \tag{6}$$

$$\sum_{j \in L_n} \sum_{k=1}^{s} x_{ij}^k \le C \qquad \forall i \in \mathbf{C} \qquad (7)$$

$$\sum_{k=1}^{s} x_{ij}^k \le 1 \qquad \forall j \in \mathbf{L}, i \in \mathbf{C} \qquad (8)$$

$$\sum_{j \in L_n} \sum_{i=1}^{c} x_{ij}^k \le \ell_n \qquad \forall k \in \mathbf{S} \qquad (9)$$

$$\sum_{i=1}^{c} \sum_{k=1}^{s} f_{ij}^k \le \kappa_j \qquad \forall j \in \mathbf{L} \qquad (10)$$

$$f_{ij}^k \le \kappa_j x_{ij}^k \qquad \forall i \in \mathbf{C}, j \in \mathbf{L}, k \in \mathbf{S} \qquad (11)$$

$$\tau_{ij}^k = \chi \frac{\lambda_j}{\kappa_j} x_{ij}^k \qquad \forall i \in \mathbf{C}, j \in \mathbf{L}, k \in \mathbf{S} \qquad (12)$$

$$0 \le \tau_{ij}^k \le T \qquad \forall i \in \mathbf{C}, j \in \mathbf{L}, k \in \mathbf{S} \qquad (13)$$

$$f_{ij}^k \ge 0 \qquad \forall i \in \mathbf{C}, j \in \mathbf{L}, k \in \mathbf{S} \qquad (14)$$

$$x_{ij}^k \in \{0,1\} \qquad \forall i \in \mathbf{C}, j \in \mathbf{L}, k \in \mathbf{S} \qquad (15)$$

$$d_i \ge 0 \qquad \forall i \in \mathbf{C} \qquad (16)$$

The objective function (1) is to determine the lowest WCETT [7]. Constraint (2) determines the maximum ETT (d_i) in a channel. Constraint (3) ensures that the received data is the same as transmitted data by those APs that neither originated the message nor the final destination in a respective session. Equations (4) and (5) indicate, respectively, the data flow for sender AP and receiver AP. These constraints guarantee the flow balance of WMN.

In terms of channel assignment, for each link, only one channel must be used (constraint (6)). Constraint (7) limits the maximum amount of channels used by an AP. Constraint (8) defines that a link j trafficking over channel i must be assigned for only one session. The total amount of links connected in a given AP n, denoted by ℓ_n, must be equal to the amount of links assigned to channels, denoted by equation (9).

Bandwidth constraints improve data flow in WMNs [5] and thus leading to cross-layer optimization. Constraint (10) refers to the total data flow on a link which can not be greater than the link capacity, while constraint (11) determines whether data flow present in a link is trafficking in a valid combination of a channel with a session. As τ_{ij}^k refers to ETT in a transmission and each ETT is equal to the product between the respective ETX, denoted by χ and the ratio between the packet size (λ_j) and the link capacity – equation (12). Constraints (13), (14), (15) and (16) limit the values assigned to decision variables. Specially, in constraint (12), ETT is described as a function of set of variables x^k_{ij}, but, if ETX (χ) is considered as a variable (not a probability), then this constraint will be non-linear. In this case, we propose a heuristic algorithm, separating the model in two subproblems – channel assignment and flow control. In this case, the algorithm is described in Figure 2.

```
Begin
  Initialize ETTs
  Repeat
    Solve Channel Assignment (Integer Programming)
    Solve Flow Control (Linear Programming)
    Updating ETTs
  Until ETTs converge
  Print cross-layer configuration
End
```

Figure 2 – Heuristic algorithm to obtain an approach solution

The subproblem of channel assignment looks for a combination of channels and sessions that facilitate data transmission without interference between them. This combination can estimate ETTs, considering initial time values that will be updated. Thereafter, the subproblem of flow control looks for the lowest value for WCETT of a given WMN based on conditions of bandwidth and link capacity by observing ETT from each link. This decomposition is accomplished by dividing the objective function (1) into two parts, where each part is used as a new objective function in each subproblem. Thus, the subproblem is defined as follows:

$$Z_c = \max \sum_{k=1}^{s} \sum_{j=1}^{\ell} \sum_{i=1}^{c} t_{ij}^{k[M]} x_{ij}^{k} \tag{17}$$

Subject to

Constraints (6), (7), (8), (9) and (15).

The objective function for channel assignment is recomposed from the sum of values of d_i (Equation (1)), combining with constraint (2), where initial parameters $t^{k[0]}_{ij} \neq 0$ are established as initial values for ETT, where will be calculated jointly with ETTs defined as variables the estimative for time values. Based on this new equation (17), this subproblem is considered as Integer Programming model, whose decision variables are represented by set x_{ij}^{k}. This subproblem must be solved before to reduce complexity of the constraint (12).

Once the values for x_{ij}^{k} are obtained, the next step is to establish satisfactory values for the other subproblem, flow control. Notice that the maximum value between channels for ETT with maximum channel gain is already defined. So, in this subproblem, the values of binary variables x_{ij}^{k} will act as parameters for constraint (12). Thus, the subproblem of flow control is defined as follows:

$$Z_f = \min \sum_{k=1}^{s} \sum_{j=1}^{\ell} \sum_{i=1}^{c} \tau_{ij}^{k[M]} \tag{18}$$

Subject to

Constraints (3), (4), (5), (10), (11), (12), (13) and (14).

Equation (18) contains only proactive times, subject to constrains of flow control and bandwidth. In this paper, the link capacity κ_j is considered as fixed values, not considering noise in the environment, to be exploited in future works. The last step of iterative process is update parameters t^{k}_{ij}, once these values are used again as parameters for other solution in channel assignment subproblem. The equation for updating of ETTs is denoted by:

$$t_{ij}^{k[M+1]} \leftarrow \gamma t_{ij}^{k[M]} + (1-\gamma)\tau_{ij}^{k[M]} \tag{19}$$

where M represents the step of iterative algorithm. This process is repeated until when the condition $\left| t_{ij}^{k[M+1]} - t_{ij}^{k[M]} \right| < \varepsilon$ is satisfied, where ε is threshold approach.

4. Numerical Results

The algorithm, presented in Figure 2, was applied on random WMNs. As a default configuration, the values for parameters established are: κ_j = 54 Mb/s; χ = 4.761905; C = 3 channels; T = 1000 ms; $\varepsilon = 10^{-5}$; γ = 0.7; λ_k = 4 Mb/s. Results are obtained on Quad Core CPU computer with RAM RAM memory of 4GB. The algorithm was implemented in C programming language and used CPLEX libraries. Results are obtained, in order to show the behavior of the model when the number of APs grows and, consequently, the number of gateways, links and sessions. In Table 3, obtained results are listed along with the respective computational time.

Table 3 – Results obtained from MILP model

N	L	S	WCETT (ms)	CPU time (s)
12	18	3	6.72	
20	3	3	1.16	-
40	21	17	44.13	-
100	179	35	149.21	55
200	572	68	303.00	209

In this table, within a realistic amount of APs (up to 40 APs), the solution has been obtained in few seconds. When the amount of APs increases to more than 100 devices, CPU time increases substantially, according to the complexity of the model. For example, in a WMN with 200 APs, there are 5,801,600 variables only for channel assignment decision.. Now, by employing a heuristic, the behavior of model is described in Table 4.

Table 4 – Results obtained from heuristic

n	*m*	*s*	WCETT (ms)	iterations	CPU time (s)	Gap (%)
12	18	3	6.30	15	-	6.3
20	3	3	1.11	13	-	4.55
40	21	17	44.07	18	-	0.12
100	179	35	149.87	15	25	0.004
200	572	68	304.35	16	165	0.004

Note that, while the number of APs increases, the gap between the optimal solution and heuristic decreases, In this table, we note the autonomy of algorithm when the number of APs has increased, in order to evaluate the performance in terms of time and memory.

This is just an example to show the how fast a model size may increase and the difficulty of proposing a model for extending the capabilities of the WMNs, if necessary.

5. Conclusion

This paper presented an approach to minimize WCETT in a WMN, analyzing the layers present in a wireless network model. A cross-layer optimization model was proposed to find a set of metrics used in different layers, in order to notice the behavior of metrics extracted from interactive actions between them.

As future work, we propose testify the heuristic, increasing non-linear constraints to simulate transmissions containing signal interferences measured by ratio between signal-noise, such as SINR. Other contribution offered by this paper is aggregate hybrid methods to reduce the number of variables to be processing simultaneously, in order to avoid the algorithm is *out-of-memory*.

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