Green Routing Algorithm for Wireless Mesh Network: A Multi-Objective Evolutionary Approach

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Abstract — Wireless Mesh Networks (WMN) is one of the technological infrastructures that provide the technical characteristics that could fulfill the requirements proposed by the Smart Cities. One of the most important challenges is designing of optimal routing protocols in this kind of networks, especially for the smart cities environment. These protocols must be efficient in the allocation and use of resources in the network and to meet the requirements of the new services in terms of Quality of Service (QoS). In this paper we propose a routing algorithm based on the Strength Pareto Evolutionary Algorithm (SPEA) which intends to build the most efficient routes taking into account the shortest path, energy consumption and QoS restrictions (delay and bandwidth). As result, the routing protocol designed could be used in unicast or multicast schemes, with or without restrictions and into centralized or decentralized environments.

Keywords— Genetic Algorithms; Multi-Objective Optimization; Strength Pareto Evolutionary Algorithm; Routing Protocol; Wireless Mesh Networks

I. INTRODUCTION

For years the growing and development of the cities were based in the endowment of hard infrastructure; however, in recent years it started a movement that conceived the inclusion of digital infrastructures and information products as an important platform for the sustainable development of the cities [1]. This movement is called Smart Cities.

The International Telecommunication Union through the Telecommunication Standardization Sector (ITU-T) define the Smart Cities as “a ‘knowledge’, ‘digital’, ‘cyber’ or ‘eco’ city; representing a concept open to a variety of interpretations, depending on the goals set out by a smart city’s planners. We might refer to a smart city as an improvement on today’s city both functionally and structurally, using information and communication technology (ICT) as an infrastructure” [2].

An important role in the new scenarios proposed for the Smart Cities, will be taken by the network infrastructures, especially by the wireless mesh networks (WMN). That could be one of the most used technologies in the communication infrastructure deployments, because this kind of wireless networks are self-configurable, self-organizing, and self-healing. Other important characteristics of the WMN are the easy deployment and maintenance, the high scalability and the low cost backhaul services for large coverage [3], [4].

Considering the characteristics listed above, the design of routing protocols for WMN are an important challenge [4], [5]. These designs must be efficient in use of the energy consumption in the network, optimizing the resource allocation and meeting the needs of users in terms of QoS. This paper presents a scalable algorithm for routing in WMN based on these requirements.

The remainder of this paper is organized as follows: Section 2 presents the related works around the routing algorithms in WMN, especially those ones based in genetic algorithms. We show our mathematical formulation approach to the routing in wireless mesh networks as a multi objective problem in Section 3. In Section 4 we propose a decentralized routing algorithm based on the Strength Pareto Evolutionary Algorithm (SPEA). The experimental scenario where the proposed algorithm was tested is presented in Section 5. Finally, Section 6 shows the conclusions and Section 7 the future works.

II. RELATED WORKS

Many routing protocols for WMN have been proposed in recent years, however a lot of them using traditional schemes design, i.e. they are optimizing only one function and other related functions are assumed as constraints in the model. Nevertheless, in the last years some researchers proposed the use of multi-objective optimization approach in order to find optimal routes that allow the compliance of all the considerations at the same time. Several works in this direction are analyzed in the following paragraphs.

Authors in [6] present a study on algorithmic aspects of the QoS routing problem. They show that the problem of finding a feasible path with only one QoS requirement, (which is described in terms of end-to-end bandwidth) is NP-complete. Yoon and Ryou propose in [7] a method for dynamically selecting path in WMN routing using genetic algorithms. They design the algorithm taking into account data loss rate, hop count, network bandwidth and load of the link in WMN. As a result, it was proved through simulations that the algorithm increases the data throughput and decreases the loss rate overall network.

In [8] Liu et al., presents a routing algorithm for WMN using the ant colony optimization (ACO) algorithm. As objective functions was selected the hop count, the congestion level and the bandwidth, therefore the authors assure the load balance on each link. The experimental results present an important reduction in the average end-to-end delay and control overhead, in addition increases the successful transfer rate.
Two different routing algorithms were proposed in [9], the first one used the Non-dominated Sorting based Genetic Algorithm-II (NSGA-II) and the second employed a Multi Objective Differential Evolution (MODE) algorithm. As objective functions they propose energy consumption and end-to-end delay in both algorithms. The simulation results show an efficient response finding the optimal routes; in addition, results demonstrate a better behavior in terms of convergence of MODE than NSGA-II.

Authors in [10] present a multicast routing algorithm based on discrete particle swarm optimization (PSO) to minimize the maximum delay, the cost of the tree and the average delay. They compare their algorithm with respect to both the Shortest Path Tree algorithm (SPT) and the constrained steiner tree algorithm (KPP). An approach using linear programming is presented in [11]. Authors propose a QoS-aware link scheduling scheme for wireless mesh networks (WMNs). The scheme allocates time slots and transmission power to the network nodes in a way that maximizes the spatial reuse of the network bandwidth, but this approach is limited to small networks because it is using a linear programming solver.

III. PROBLEM STATEMENT

In this work we design a routing algorithm for Wireless Mesh Network according to the challenges that propose the smart cities environment. The main objective of this algorithm is that any node could find an optimal route to one destination node (unicast) or to many destination nodes (multicast) doing an efficient use of the energy, decreasing the possibility of packet loss and guaranteeing the provision of QoS over the path, specifically ensuring a maximum delay and minimum bandwidth consumption. Given that, our problem will involve more than one objective function that sometimes could be in conflict, i.e., a shortest path between two nodes (in terms of number of hops) could have the highest delay, therefore we use a multi-objective approach in order to find an optimal set of solutions that holds a trade-off between all proposed objective functions.

A. Network model

We assume that WMN have symmetrical links between the different nodes; therefore we could model as non-directed graph. We represent the input graph as \( G(N,L) \), where \( N \) is the set of nodes and \( L \) is the set of links. Among the nodes, we have a source \( s \in N \) (ingress node) and some destinations \( T \) (the set of egress nodes). Let \( t \in T \) be any egress node. Let \((i,j)\) be the link from node \( i \) to node \( j \).

In order to get an algorithm to solve our problem, we propose a multicast multi-objective mathematical model instead of unicast model. The unicast case is in fact the same as the multicast but reducing the set \( T \) to only one element. In Table I we present all parameters involved in our model.

B. Mathematical model: Decision Variable

The path building between two nodes is represented as a sequence of used links that meets with the different optimization criteria that has been defined. In order to represent this path we define a binary decision variable \( X_{ij}^t \), that will tell us whether a particular link \((i,j)\) is used (or not) in the path to destination \( t \). The variable is defined as follows:

\[
X_{ij}^t = \begin{cases} 
1, & \text{if the } (i,j) \text{ link is used in the path with destination } t \\\n0, & \text{otherwise} 
\end{cases} \tag{1}
\]

C. Mathematical model: Objective Functions

We described below the 4 objective functions that we use in the proposed mathematical model for the routing algorithm.

1) Hops Count
The hops count function is the main function of many routing algorithms. This function represents the number of links through which packets must pass from source to the set of destination nodes. The purpose of minimizing function (2) is finding the shortest path between any pair of nodes.

\[
f_{\text{hop}} = \min \sum_{t \in T} \sum_{(i,j) \in L} X_{ij}^t \tag{2}
\]

2) Energy Consumption
As WMN could be composed by heterogeneous nodes and each one of these nodes in the network could have different energy consumption in both transmission and reception. Given the nature of WMN, some nodes belong to this network could be mobiles phones, sensors, laptops, etc., therefore the proposed routing algorithm, in order to reduce power consumption, should select the path with the lower overall energy consumption to increase the battery life of these kind of devices.

The objective function (3) takes into account both the energy consumption used by source node in the transmission process and the energy used by the destination node in the reception process, over the entire path.

\[
f_{\text{pc}} = \min \left( \sum_{t \in T} \sum_{(i,j) \in L} P_{il} \cdot X_{ij}^t + \sum_{(i,j) \in L} P_{lj} \cdot X_{ij}^t \right) \tag{3}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N )</td>
<td>Set of nodes</td>
</tr>
<tr>
<td>( L )</td>
<td>Set of links</td>
</tr>
<tr>
<td>( T )</td>
<td>Set of egress nodes or any egress node</td>
</tr>
<tr>
<td>( i )</td>
<td>Index for the source node of the link ( l_i ), where ( i \in N ) and ( l_i \in L )</td>
</tr>
<tr>
<td>( j )</td>
<td>Index for the destination node of the link ( l_j ), where ( j \in N ) and ( l_j \in L )</td>
</tr>
<tr>
<td>( P_{il} )</td>
<td>Denotes the power consumption of the node ( i ) to transmit data (dBm)</td>
</tr>
<tr>
<td>( P_{lj} )</td>
<td>Corresponds the power consumption of the node ( j ) to receive data (dBm)</td>
</tr>
<tr>
<td>( d_{ij} )</td>
<td>Represents the distance between the nodes ( i ) and ( j ) (meters)</td>
</tr>
<tr>
<td>( f_i )</td>
<td>Symbolizes to the transmission frequency between the nodes ( i ) and ( j ) (Hz)</td>
</tr>
<tr>
<td>( c )</td>
<td>Constant that represents the speed of light in a vacuum (m/s)</td>
</tr>
<tr>
<td>( F_{\text{SFL}} )</td>
<td>Represents the free space loss between the nodes ( i ) and ( j ) (dB)</td>
</tr>
<tr>
<td>( D_{\text{min}} )</td>
<td>Corresponds to the delay in the transmission over the link ( l_i ) (ms)</td>
</tr>
<tr>
<td>( BW_{ij} )</td>
<td>Symbolizes the minimum delay in in the transmission over the path (ms)</td>
</tr>
</tbody>
</table>
3) Free Space Loss
This function defines the signal strength loss in free space conditions. This loss is directly related with the distance between the nodes and the transmission frequency.

\[ FSL_{ij}(dBm) = 10 \log_{10} \left( \frac{1000 \cdot 4 \cdot \pi \cdot d_{ij} \cdot f_j}{c} \right)^2 \] (4)

The aim of the following objective function (5) is the minimization of the maximum overall loss in the path.

\[ f_{los} = \min \sum_{(i,j) \in L} FSL_{ij} \cdot x_{ij}^t \] (5)

4) Delay
The final objective function is related with the Delay in the transmission process between the source and destination nodes. We introduce this function (6) that seeks the minimum overall delay in the path.

\[ f_{delay} = \min \sum_{(i,j) \in L} D_{ij} \cdot x_{ij}^t \] (6)

D. Mathematical model: Flow conservation and QoS
Constraints
In this multi-objective model we have considered several constraints for ensure the consistence of the mathematical model and the Quality of Service (QoS) requirements. It is important to remark that for these restrictions we define that the source node is represented by \( s \) and the destination node by \( t \).

1) Decision variable
As we defined previously the decision variable \( x_{ij}^t \) is binary, so that its values can only be 0 or 1.

\[ x_{ij}^t = \{0,1\} \] (7)

2) Flow conservation
The aim of the flow conservation constraint is to guarantee that the path built between the source node \( s \) and the destination node \( t \) is valid. That’s mean that all data packets generated by \( s \) can reach \( t \).

The first restriction (8) ensures that there exists only one path from the node \( s \) to each destination \( t \in T \). The next restriction (9) aims to assure that exist only one path to the node \( t \). Finally, the last constraint (10) insures that all the packets that arrive to an intermediate node (node that not is \( s \) or \( t \)), leave the node through another link.

\[ \sum_{(i,j) \in L} x_{ij}^t = 1, \quad \forall t \in T, i = s \] (8)

\[ \sum_{(i,j) \in L} x_{ji}^t = -1, \quad \forall t \in T, i = t \] (9)

\[ \sum_{(i,j) \in L} x_{ij}^t - \sum_{(i,j) \in L} x_{ji}^t = 0, \forall t \in T, i \neq s, i \neq t \] (10)

3) Quality of Service
In order to guarantee the Quality of Service required for the transmission of some specific services in the network, we introduced two QoS constraints in the model. The first related with the bandwidth and the second with the delay.

\[ \min \left( BW_{ij} \left| x_{ij}^t = 1 \right. \right) \geq BW_{min}, \quad \forall t \in T \] (11)

\[ \sum_{(i,j) \in L} D_{ij} \cdot x_{ij}^t \leq D_{min}, \quad \forall t \in T \] (12)

The restrictions (11) and (12) ensure that at least the required bandwidth (\( BW_{min} \)) is available over all the links involved in the path for a given services and that the sum of the delay through the path is less than the delay required by the service (\( D_{min} \)), respectively.

IV. Proposed Algorithm
From the point of view of routing protocols, our algorithm can be implement as a table-driven (pro-active) routing protocol due to routes to all destinations within the network are known and maintained before use. In order to get the set of routes for each node to the other ones, we select a Multi-Objective Evolutionary Algorithms (MOEA) to solve the Multi-Objective mathematical model. Note that our algorithm based on MOEA works in a distributed way because each node can compute routes from itself (source node) to any other node (set \( T \) of nodes) following the mathematical model. We choose MOEA because we could find multiple optimal solutions in one run simulation and its complexity is only depending of MOEA parameters [12].

A. Genetic Approach to solve the mathematical model
The core of the routing protocol is the algorithm to find routes by solving the mathematical model. The MOEA chosen for this implementation is the Strength Pareto Evolutionary Algorithm (SPEA) proposed by Zitzler and Thiele in [13]. This algorithm implements an efficient elitism strategy that could maximize the number of solutions of the Pareto optimal set found, minimize the distance between the Pareto front found and the global Pareto front (assuming we know it) and finally maximize the distribution of solutions found [14].

The pseudo-code of the SPEA implemented is presented in Fig. 1.

```
begin
Generate a random population \( P_0 \)
while (not max number of generation)
    Evaluate population according objective function
    Calculate the fitness of each of the individuals
    Classification Population based on fitness \( (P_i, \hat{P}_i) \)
    Generate New Population \( P_{i+1} \)
    Apply Binary Tournament Selection
    Apply Crossover Operator
    Apply Mutation Operator
endwhile
Find Pareto Optimal Set
end
```

Fig 1. SPEA algorithm pseudo-code
D. Comparison Operator

In order to verify the quality of the solutions found by the MOEA, we design the chromosome as the set of the entire path between one source node \( s \) and all the other nodes in \( N \) (See Fig 2). The single-point crossover strategy proposed in [12] was implemented as crossover operator. In this strategy the algorithm calculate the minimum size of the paths in each parent chromosomes and generate a randomize number in this interval, this generated number represent the cut point of both chromosomes. Then, the right side of both parents is exchanged, generating two new solutions. Fig. 3 shows an example of the crossover operator.

In relation with the mutation function, we define two different ways to calculate the new chromosome depending of the mutation probability. The first one selects a random number of paths in the parent chromosome; these paths are recalculated using a random path finder generating a new chromosome. The second way is to generate a completely new chromosome. Fig. 4 shows an example of the mutation operator. It is important to note that for any new solutions found, we verify that it is a feasible solution.

V. EXPERIMENTAL RESULTS

The flexibility of our mathematical model permits to use the proposed routing algorithm in different ways. In this section we will show different scenarios to compare the solutions got by our algorithm with the traditional Shortest Path Algorithm (SPA). The figure 5 presents a typical topology for WMN composed by different wireless technologies as WiMax (802.16e), Wi-Fi (802.11 a, b, g, n) and Bluetooth (802.15). The values of bandwidth, delay, frequency, distance coverage and power consumption for each link, which were generated randomly using as a reference the data given in [16] [17] and they are showed in the Tables II and III.

In order to verify the quality of the solutions found by the MOEA, we write and execute the mathematical programming model of the problem using the General Algebraic Modeling System (GAMS) [18].
A. Experimental Scenario 1: Find optimal routes without QoS

When we don’t include the restrictions to solve the mathematical model, the resulting solutions given by our algorithm are the set of routes between the source node $s$ and the destination nodes $t \in T$ that permit to minimize all the objective functions holding a trade-off between them. In the experimental scenarios, we selected node 14 as source and the rest of nodes of the network as destination nodes (set $T$). The MOEA used an initial population of 100 and it runs 100 generations.

Using the above configuration, we found 11 different solutions. Table IV shows the optimal values when we individually optimize each objective function using GAMS. Table V shows several solutions from our algorithm and their relative errors for each objective function.

In general, we observed that relative error of the MOEA’s solutions is less than 15% in most cases. However, although the FSL objective functions get the worst results, sometimes (e.g. solution 10) we get values with relative error under 10%. Table VI compares the best route obtained using the shortest path algorithm (SPA) and one of the obtained solutions using our proposal.

![Fig 5. Backhaul Wireless Mesh Network](image)

![Fig 6. Representation Graph of the Backhaul Wireless Mesh Network](image)
B. Experimental Scenario 2: Find optimal routes with QoS (delay)

In this scenario, we added QoS requirements for the resulting paths. The required QoS in the network core (nodes 1, 2, 3 and 4) is the necessary for VoIP services [19]; it is presented in the table VII. With the initial topology configuration parameters, we observe that all routes using the Shortest Path Algorithm (SPA) holds the round trip delay for VoIP services in the core (look the routes of the SPA from table VI) less than 200ms. Note that the bandwidth requirement in our topology is also satisfied.

Now, when congestion problems appear on the network, the SPA could not give us the best routes that ensure QoS. Suppose that the link 3-4 increases its delay from 102 to 150 ms, then the results given for the SPA leave some routes through the link 3-4 and the QoS for VoIP in the core is not ensure. On the contrary, when our algorithm with QoS detects that restriction, it creates paths which do not use the link 3-4 and it permits that all packet from the input core node 3 (the source node is 14) to nodes 1, 2, 4 have paths with delay equal to or less than 200ms: the paths 3-2-1 and 3-2-4 have a delay of 195ms and 200ms, respectively. Table VIII shows the results given for our algorithm.

C. Experimental Scenario 3: Find optimal routes with QoS (Power Consumption)

Suppose that the links 1-7, 7-2 and 3-2 are replaced by fiber optic links. Following the results in [20], we can transport 1Gbps using only 7mW (8.45dBm approx.). Our proposed algorithm, detecting this new parameters, it creates routes that pass through those links and reduce the general power consumption. Table IX shows the results using our proposal and the Table X shows the comparison between the values for each objective function when we individually minimize the number of hops (SPA) and power consumption with respect to our algorithm solutions.

VI. CONCLUSIONS

We have showed that our proposed model and algorithm are good alternatives to implement fast and efficient routing algorithms for WMN. The independence of the algorithm complexity with respect to the number of nodes/links along with the possibility to get multiple solutions in one execution permit us to find (sub) optimal routes with any kind of QoS restrictions. In addition, we can use the mathematical model either in unicast or multicast schemes, with or without restrictions and into centralized or decentralized environments.
TABLE X
COMPARISON BETWEEN OUR ALGORITHM AND OTHER APPROACH IN THE SCENARIO 3

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Value of Objective Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOEA for QoS routing</td>
<td>Hops: 83</td>
</tr>
<tr>
<td></td>
<td>Delay (ms): 4653</td>
</tr>
<tr>
<td></td>
<td>FSL (dB): 6703.51</td>
</tr>
<tr>
<td></td>
<td>Power Consumption (dBm): 5108.27</td>
</tr>
<tr>
<td>Minimizing number of hops (SPA)</td>
<td>Hops: 81</td>
</tr>
<tr>
<td></td>
<td>Delay (ms): 4451</td>
</tr>
<tr>
<td></td>
<td>FSL (dB): 6535.62</td>
</tr>
<tr>
<td></td>
<td>Power Consumption (dBm): 5571.24</td>
</tr>
<tr>
<td>Minimizing power consumption</td>
<td>Hops: 87</td>
</tr>
<tr>
<td></td>
<td>Delay (ms): 5039</td>
</tr>
<tr>
<td></td>
<td>FSL (dB): 7039.27</td>
</tr>
<tr>
<td></td>
<td>Power Consumption (dBm): 4680</td>
</tr>
</tbody>
</table>

VII. FUTURE WORKS

We see that the FSL function got the worst values and it shows that we need to include new heuristics into the MOEA evaluative operators that enable us find routes with better FSL values. In addition to this, it could be interesting to verify if it is possible to improve the performance of our algorithm using more heuristics such as evolutionary operators in order to get better results in the rest of objective functions without increasing the time or memory complexity. It is important to verify the performance of our algorithms on large scale networks. It will be interesting to compare our proposal with respect to SPA and other MOEAs on those networks.

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REFERENCES