

# Flow Aggregation for Energy-Aware Ad-Hoc Wireless Networks Respecting QoS Provisions

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**Abstract**—Emerging communication technologies are now leading developers to design IT systems taking into count their energy-related considerations. Much research performed in the area of ad-hoc wireless networks tends to distribute the flows over all nodes of the network, which increases the amount of energy consumed by each node and reduces longevity of the network. To overcome these problems, this paper seeks to aggregate a set of flows within a number of nodes that is as low as possible in order to be capable of routing those flows. This proposal allows to maximize the number of network nodes that may be turned off. The proposed solution was formulated as an integer linear programming (ILP) problem using a set of energy and quality of service (QoS) constraints. This formulation minimizes the total energy consumed by the nodes to construct a topology network that is capable of meeting QoS requirement for a set flows inserted into the network. To evaluate the efficiency of the proposed model, a performance-based comparison was conducted with another routing model. The simulation results show that the proposed model offers better performance in terms of global energy consumption and network load.

**Keywords**—*ad-hoc wireless networks, flow's aggregation, global energy consumption, ILP, QoS provisions.*

## 1. Introduction

Ad-hoc wireless networks with multi-hop coverage extensions have been the subject of intense investigation over the past decade [1]. Flexibility of this specific type of a wireless network has been taken advantage of in different areas, such as military, disaster recovery and vehicular communication [1]–[3]. An ad-hoc wireless network is a group of nodes that can move dynamically and form a network without using any fixed infrastructures. Each node within this network operates both as a communication end-point and a router [4].

Extensive research has been conducted to address many issues, including quality of service (QoS) considerations. Most of the existing work proposes techniques to route flows more efficiently, such as admission control [5], coding packets to reduce the number of transmissions [6] and

QoS routing which has been studied recently [7], [8]. The last technique requires not only finding a route from a source to a destination, but also calls for meeting end-to-end QoS requirements, often expressed in terms of bandwidth and delay [9]. These two parameters are particularly dependent on the topology of the network [8]. Energy management is another issue which has recently emerged in network topology-related considerations.

An ad-hoc wireless network consists of nodes, with each of them being usually powered by a limited capacity battery. Therefore, power consumption is a major concern when determining a network topology that meets QoS requirements. Several studies have already been performed with a view of satisfying those objectives [10]–[12]. The majority of these studies have proposed algorithms that make numerous assumptions about the computing power of the nodes to reduce energy consumption locally. Classic approaches are usually based on equitable distribution of load between all nodes, so that their batteries are exhausted uniformly in order to prevent a node from dying prematurely because of its overuse [13]. We also notice that energy consumption of a node may be attributed to several phenomena, including those related to the wireless interface. Therefore, it is more efficient to switch off a node as often as possible, since this decreases energy consumption and increases network lifetime.

In [14], [15], the authors proposed a solution to determine the transmission power  $p_i$  for each node to minimize the amount of energy consumed by all nodes within the network while meeting end-to-end QoS constraints in terms of delay and bandwidth. The present work aims at extending this solution by adding a flow aggregation technique to increase the number of unused nodes, hence significantly reducing global energy consumption within the network. The core idea is to aggregate flows into a specific sub-set of nodes of the network, in order to minimize the number of nodes required to route a set of flows. Given a set of nodes in a two-dimensional surface and QoS requirements applicable to those flows, this idea consists in identifying a network topology that minimizes global energy consumption while simultaneously meeting QoS requirements which are

the same as the ones that need to be respected in [14], [15]. Integer linear programming is used to formulate the problem. A branch-and-bound mathematics technique was exploited to arrive at the optimal solution.

The remaining sections of this paper are organized as follows. Section 2 presents existing research findings related to energy management in ad-hoc wireless networks. Section 3 recalls the model used for ad-hoc wireless networks and describes the proposed formulation with its specifications. The simulation setup and results are detailed in Section 4. Section 5 summarizes the work and addresses research perspectives related to the model proposed.

## 2. Related Work

When discussing the issue of energy consumption in ad-hoc wireless networks, topology control is one of the most important energy management techniques that needs to be taken into consideration [16]. Much has already been proposed in this area, with a view to vary the transmission power of nodes – a solution which implies a modification to the nodes' transmission range and neighborhood. The first study in this field [17] showed the relationship between throughput and forward progress (transmission range), with each node being able to adjust its transmission power to reduce interference and, hence, achieve higher throughput. In [18], the authors propose a distributed topology control algorithm for each node in a packet radio network to adjust its transmitting power and control its logical neighbors in order to construct a reliable, high-throughput topology. Both studies failed to take into account minimizing energy consumption.

Most of the work related to constructing and maintaining a network topology with the required connectivity has relied on minimizing energy consumption. Paper [19] proposes two centralized algorithms that may be used in static networks. These algorithms aim at constructing a connected network, while minimizing the maximal transmitting power for each node. For mobile networks, two other distributed heuristics were presented, such as local information no topology and local information link state topology [19], to adaptively adjust node transmit powers in response to topological changes. The issue of finding an optimal topology for Bluetooth wireless personal area networks is discussed in [20]. An optimal topology that provides complete network connectivity and meets traffic requirements and system specification constraints is found. Moreover, this topology minimizes traffic load of the most congested node in the network. In [14], the energy-efficient QoS topology control problem was discussed to identify a network topology that may meet QoS requirements in terms of delay and bandwidth, simultaneously minimizing the maximum transmitting power of nodes.

In [21], a minimum spanning tree (MST)-based algorithm is developed. The idea is that each node constructs its local minimum spanning tree independently and only keeps on-tree nodes that are one-hop away, i.e. are its neighbors in

the final topology. In [22], Li *et al.* propose a cone-based distributed topology-control algorithm which is based on the geometrical position of nodes instead of the global connectivity of the graph. The basic idea of the algorithm is that a node can adjust its transmission power such that it has at least one neighbor around it. A set of optimizations was also proposed in this work that further reduces power consumption and retains network connectivity. However, traffic is not taken into account in this algorithm. So to overcome this problem, Martin *et al.* [23] develop a traffic-based topology control algorithm to optimize global energy consumption without degrading QoS provisions, and to reduce interference based on existing flows.

Other studies have discussed the problem of energy consumption of ad-hoc wireless networks. Several energy-aware routing algorithms are developed and their effects on various QoS parameters intrinsic to traditional networks, such as delay, bandwidth and packet loss, are discussed in [24]. This study shows that energy-efficient algorithms usually increase overall longevity of the network by efficiently using energy resources of every node. To determine the optimal transmission power of nodes, Rashmi *et al.* propose in [25], a clustering-based scalable topology control method (optimized power control), aiming at keeping the network connected throughout the communication. The effects of this method on network parameters, such as average transmission power per node, total energy consumption and network delay, are studied. The proposed approach is based on topology control, and its simplicity makes it suitable for use to enhance the performance of other network scenarios, such as WSNs, VANETs and CRNs.

In [13], the authors prove that the distribution of load over a large number of nodes forces them to remain active throughout the communication process, which results in very low global energy consumption. Then, it is necessary to exploit mechanisms that allow to switch off unused nodes for good management of network resources.

## 3. Network Model

An ad-hoc wireless network is modeled by a graph  $G = (V, E)$ , where  $V$  is the group of  $N$  nodes and  $E$  is the group of undirected links between those nodes. A pair of nodes  $(i, j)$ , where  $i$  and  $j$  belong to  $V$ , is in  $E$  if there exists a link between nodes  $i$  and  $j$ . This means that the node  $i$  can transmit data at a certain distance to the node  $j$ . Thus, a link  $(i, j)$  exists if  $j$  is in the transmission range ( $TR$ ) of node  $i$ .

### 3.1. Assumptions

In this paper, the following assumptions are made in the formulation of the problem. We adopt the widely used transmitting power model for radio networks [26]:

$$P_{ij} = (d_{ij})^\alpha, \quad (1)$$

where:  $P_{ij}$  is the transmitting power needed for source node  $i$  to reach destination node  $j$ ,  $d_{ij}$  is the distance between nodes  $i$  and  $j$ ,  $\alpha$  is a parameter typically assuming a value between 2 and 4, depending on the characteristics of the communication medium.

The data is considered to be able to travel over multiple hops in the network to reach its destination. The energy is consumed only by those nodes that transmit data.

Let  $p_i$  denote the transmitting power of node  $i$ . Each node is assumed to be able to adjust its power level, but not exceed maximum power  $P_{max}$ . That is,  $0 \leq p_i \leq P_{max}$  for  $1 \leq i \leq N$ . Communication between two nodes depends on their distance. There is a link  $(i, j) \in E$  if and only if  $p_i \geq (d_{ij})^\alpha$  and  $p_j \geq (d_{ij})^\alpha$ .

The total energy cost,  $P_{total}$ , is the energy consumed by all active nodes in the network. The  $P_{total}$  formula is:

$$P_{total} = \sum_{i=1}^N p_i. \quad (2)$$

Each node can send signals to its neighbors in a conflict-free fashion. Thus, signal interference is not considered in this paper. Some protocols and methods have been proposed in the literature [28], [27] taking into account interference in radio transmissions.

### 3.2. Bandwidth and Delay Analysis

Each node in the network has a bandwidth capacity  $B_i$  that is shared for both transmitting and receiving signals. In other words, the total bandwidth for transmitting signals plus the total bandwidth for receiving signals at each node shall not exceed  $B_i$ .

Delay  $\Delta$  of each of flow  $f$  is the maximum number of hop-counts in the path from source node  $S_f$  to destination node  $D_f$ , i.e.

$$\Delta = \max_{f \in F} L_f, \quad (3)$$

where  $L_f$  is the number of hop-counts from source node  $S_f$  to destination node  $D_f$  for each flow  $f$  and  $F$  is the set of flows.

### 3.3. Solution

The objective of the study is to minimize the global energy consumption of ad-hoc wireless networks, which is the sum of energy consumed by all active nodes in the network. To reach this objective, we have to minimize the number of used nodes in order to switch off a maximum number of unused nodes. This section describes an extended approach that is based on flow aggregation.

To model the problem, the integer linear programming technique is used. The optimal solution of the ILP program is obtained using a branch-and-bound algorithm. This approach was developed for solving discrete and combinatorial optimization problems. Combinatorial optimization problems were used to choose the best combination out of

all feasible combinations. On the other hand, discrete optimization problems are those in which the decision variables assume values from a specified set. Most of these problems can be formulated as integer programs [29]. The essence of the branch-and-bound approach is the following observation. In the total enumeration tree, at any node, if it can be shown that the optimal solution cannot occur in any of its descendants, then there is no need to consider those descendant nodes. Hence, the tree can be pruned at this node. If enough branches are pruned in this way, the tree can be reduced to a computationally manageable size. Thus, the branch-and-bound approach is not a heuristic or approximating procedure, but an exact method that finds an optimal solution [13].

### 3.4. Problem Specification

To formulate our problem, a set of optimization parameters and variables was defined and is presented below:

Given:

- $V$  – set of  $N$  nodes and their locations,
- $B_i$  – total available bandwidth at node  $i$ ,
- $W_{ij}$  – total available bandwidth at link  $(i, j)$ ,
- $F$  – set of flows,
- $(S_f, D_f)$  – source and the destination of flow  $f$ ,
- $\lambda_f$  – traffic requests for each flow  $f$ ,
- $\Delta_f$  – maximally allowed delay for each flow  $f$ .

Decision variables:

- $x_i$  – Boolean variable which is equal to 1 if the node  $i$  is used, and 0 otherwise,
- $X_{ij}$  – Boolean variable which is equal to 1 if there is a link from node  $i$  to node  $j$ , and 0 otherwise,
- $X_{ij}^f$  – Boolean variable which is equal to 1 if the link  $(i, j)$  is used to route flow  $f$ , 0 otherwise,
- $M_{ij}$  – reserved bandwidth at link  $(i, j)$ ,
- $p_i$  – transmitting power consumed by node  $i$ .

### 3.5. Problem Formulation

The following problem formulation is proposed as an optimal solution for routing a set of flows, minimizing the number of nodes used while meeting end-to-end QoS constraints in terms of delay and bandwidth.

$$\min \sum_{i=1}^N p_i, \quad (4)$$

s.t.

$$X_{ij} = X_{ji}; \quad \forall (i, j) \in E, \quad (5)$$

$$X_{ij} = \begin{cases} 1 & \text{if } d_{ij} \leq TR ; \forall (i, j) \in E \\ 0 & \text{otherwise} \end{cases}, \quad (6)$$

$$M_{ij} \leq W_{ij} ; \forall (i, j) \in E, \quad (7)$$

$$0 \leq p_i - \sum_{j=1}^N P_{ij} \cdot X_{ij}^f \leq P_{max} ; \forall f \in F, \forall i \in V, \quad (8)$$

$$\sum_{i=1}^N X_{ij}^f - \sum_{k=1}^N X_{jk}^f = 0 ; \forall f \in F, \forall j \in V - (S_f, D_f), \quad (9)$$

$$\sum_{i=1}^N X_{ij}^f = 0 ; \forall f \in F, j = S_f, \quad (10)$$

$$\sum_{i=1}^N X_{ji}^f = 1 ; \forall f \in F, j = S_f, \quad (11)$$

$$\sum_{i=1}^N X_{ji}^f = 0 ; \forall f \in F, j = D_f, \quad (12)$$

$$\sum_{i=1}^N X_{ij}^f = 1 ; \forall f \in F, j = D_f, \quad (13)$$

$$\sum_{f \in F} \lambda_f \cdot X_{ij}^f = M_{ij} ; \forall (i, j) \in E, \quad (14)$$

$$\sum_{j=1}^N X_{ij}^f \leq 1 ; \forall f \in F, \forall i \in V - D_f, \quad (15)$$

$$\sum_{(i,j) \in E} X_{ij}^f \leq \Delta_f ; \forall f \in F, \quad (16)$$

$$\sum_{f \in F} \sum_{i=1}^N \lambda_f \cdot X_{ij}^f + \sum_{f \in F} \sum_{k=1}^N \lambda_f \cdot X_{jk}^f \leq B_j ; \forall j \in V, \quad (17)$$

$$x_i = \begin{cases} 0 & \text{if } M_{ij} = 0 ; \forall (i, j) \in E \\ 1 & \text{otherwise} \end{cases}, \quad (18)$$

$$u_i^f - u_j^f + |V| \cdot X_{ij}^f \leq |V| - 1 ; \quad \forall f \in F, \forall (i, j) \in E [i \neq S_f, j \neq D_f], \quad (19)$$

with

$$x_i \in \{0, 1\} ; \forall i \in V$$

$$X_{ij} \in \{0, 1\} ; \forall (i, j) \in E$$

$$M_{ij} \in \mathfrak{R}^+ ; \forall (i, j) \in E$$

$$u_i \in \mathfrak{R}^+ ; \forall f \in F, \forall i \in V - S_f$$

Remarks:

- formula 4 – is the objective function which aims at minimizing the sum of energy consumed by all nodes in the network,
- formula 5 – is the constraint that ensures that each link, is symmetric; it corresponds to two directed links,
- formula 6 – is the constraint that establishes the links between nodes in the network,

- formula 7 – is the constraint that ensures that the reserved bandwidth at the link does not exceed the total available bandwidth at the same link,
- formula 8 – is the constraint that defines the relations between the transmitting power consumed by each node and the decision variable  $X_{ij}^f$ ,
- formula 9 – is the constraint that ensures the flow conservation. It means that each intermediate node receiving a flow retransmits it to one of its neighbors,
- formula 10 – is the constraint that avoids routing a flow such that it returns to its source,
- formula 11 – is the constraint that avoids routing a flow such that it returns to leaves its destination,
- formula 12 – is the constraint that forces the source  $S_f$  to transmits flow  $f$  via one of its outgoing links,
- formula 13 – is the constraint that forces the destination  $D_f$  to receives flow  $f$  from one of its ingoing links,
- formula 14 – is the constraint that focuses on aggregation: the reserved bandwidth at a link is the sum of the bandwidth reserved by each flow at that link,
- formula 15 – is the constraint that represents the single path constraint, that is a flow should not be split in several paths,
- formula 16 – gives the delay constraint,
- formula 17 – is the constraint that ensures that the total transmission and reception of flows at a node do not exceed the total available bandwidth at this node,
- formula 18 – is the constraint that determines the state of each node (used or unused),
- formula 19 – is the constraint that is added from the traveling salesman problem [30] to prevent any loops in the final solution.

## 4. Experiments

In this section, simulation experiments are conducted to highlight the pertinence of the proposed solution in comparison with the performance of two other models. The first one is Jia *et al.* [14], while the other is Routing-IP [15]. On the other hand, the performance of flow aggregation is also shown in terms of global energy consumption.

### 4.1. Simulation Setup

The results obtained during simulations performed for Jia and Routing-IP models (non-splittable traffic) are presented and discussed below. All these models are formulated as ILP. To compute the solution for these ILP problems,

many tools can be employed, such as Matlab, LPSolve, CPLEX, etc. In this case, the solver software CPLEX (IBM ILOG CPLEX version: 12.8.0.0) is used. As a hardware platform, PC with 4 GB RAM and Intel 2 GHz Core i3 processor is used.

Random connected graphs are generated and the number of nodes used is counted after a set of flows is inserted. Then, specific requirements of each flow are determined in terms of delay and bandwidth, source  $S_f$  and destination  $D_f$  of the flow are selected randomly, so that they are more than one-hop neighbors.

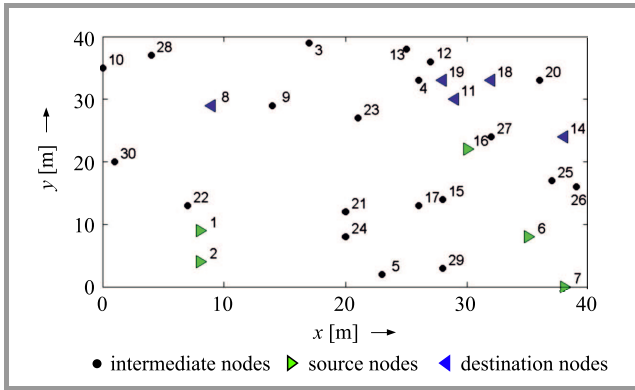


Fig. 1. Base network number  $N = 30$  in area  $40 \times 40$  m.

Random networks of 30 nodes were established in a two-dimensional free space of  $40 \times 40$  m (Fig. 1), with the nodes having a transmission range  $TR = 20$  m such that each node has at least one neighbor, and the links have a capacity of  $W_{ij} = 5 \cdot 10^3$  units. All network nodes have the same total bandwidth of  $B_i = 5.5 \cdot 10^4$  units. To assign traffic requests  $\lambda_f$  to each flow, a random normal distribution function with variance equal to  $0.5\mu_m$  was used ( $\mu_m$  is the mean value of the normal distribution function). The average bandwidth requirement per flow is  $\mu_m$ . The maximum value which we set for the flow hop-count is  $\Delta_f = 2N/15$ . Parameter  $\alpha$  in the power model is set to 2 and 4, i.e.  $P_{ij} = d_{ij}^\alpha$ , for  $2 \leq \alpha \leq 4$ .

#### 4.2. Simulation Results

The first experiment is to compare the resulting topologies for the proposed solution with two other models. Five flows are inserted into the input network, as shown in Fig. 2. Delay constraint  $\Delta_f$  for the flow is set to four. The average traffic amount per flow is  $0.02B_i$ . The routing information for each model is reported in Table 1.

Figure 2 represents a specific case where five flows are routed using Routing-IP, Jia and the proposed model. When routing is performed with the use of the Jia model, the routes are more scattered and thus more nodes have to be used. This is due to the nature of the Jia model which does not take into account the constraint of total bandwidth available at the links. The problem is that the model simply attempts to find the network topology such that all flows can be routed and the total energy consumed by all

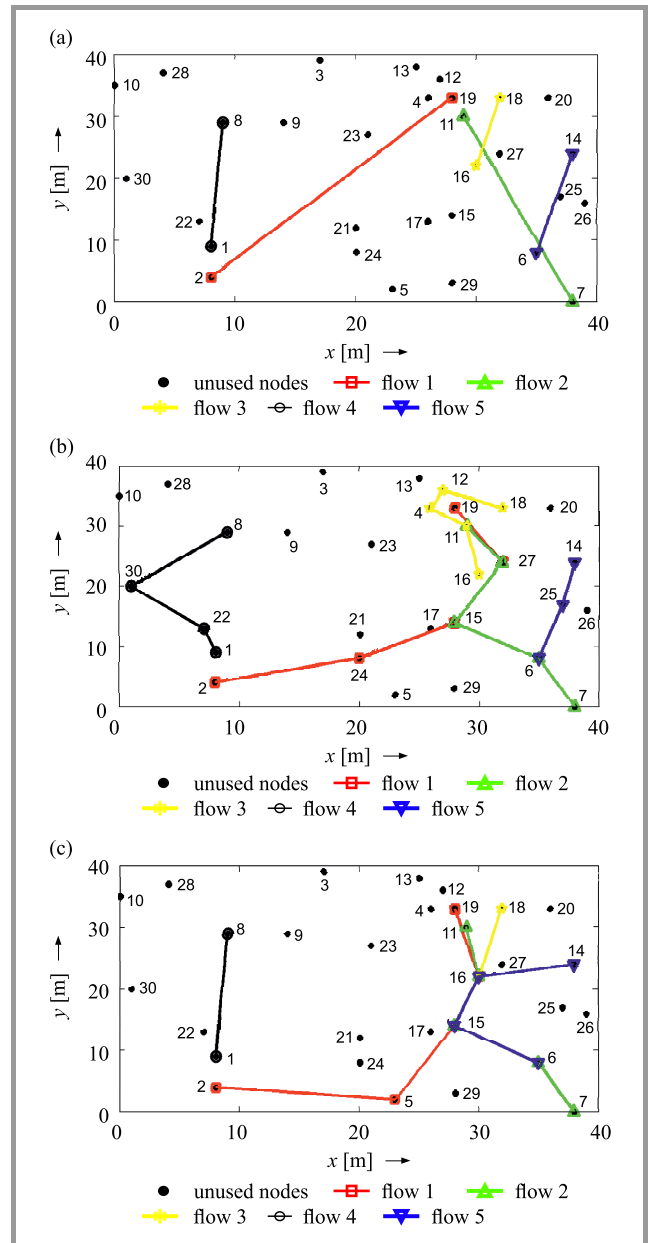


Fig. 2. Links used to route five flows with models: (a) Routing-IP, (b) Jia's, (c) proposed.

nodes is minimized. The routing solution obtained with the use of the Routing-IP model generates routes for the same set of flows, but these routes comprise fewer hops to reach the destination with long distance links, which results in a much higher  $P_{total}$ . This is due to the last model which does not take into account the transmission range constraint. This means that each node can communicate with any other node in the network without any constraints. With the proposed solution based on flow aggregation, the same set of flows has been routed over a limited number of nodes while providing the same QoS. In the example, approximately 33% of the nodes used in the Jia model can be switched off.

Another interesting point to note is that the value of the  $P_{total}$  objective function is different in all models, as shown

Table 1  
Flows and routing information

$S_f$	$D_f$	$\lambda_f$	Routing-IP model	Jia's model	Proposed model
2	19	1100.8	2 → 19	2 → 24 → 15 → 27 → 19	2 → 5 → 15 → 16 → 19
7	11	1097.6	7 → 11	7 → 6 → 15 → 27 → 11	7 → 6 → 15 → 16 → 11
16	18	1101.4	16 → 18	16 → 11 → 4 → 12 → 18	16 → 18
1	8	1102.1	1 → 8	1 → 22 → 30 → 8	1 → 8
6	14	1091.5	6 → 14	6 → 25 → 14	6 → 15 → 16 → 14
$P_{total}$ [J]			$3.4 \cdot 10^3$	$2.04 \cdot 10^3$	$0.8 \cdot 10^3$

Table 2  
Parameter values for the second experiment

Parameter	Value
$N$ size	30
$F$ inserted	1, 2, 3, 4, 5, 6, 7, 8
$B_i$	$5.5 \cdot 10^4$
$B_{ij}$	$5 \cdot 10^3$
$\Delta_f$	$2N/15$
$\mu_m$	$0.02B_i$
$\alpha$	2

in Table 1. This is due to the manner in which the power cost of the nodes is calculated in all formulations. In the current formulation used in the current study, the power cost is the corresponding element from the power matrix – constraint (8) in Subsection 3.5 – which defines the relations between the transmitting power  $p_i$  and variable  $X_{ij}^f$ . In Jia and Routing-IP formulations, the same constraint is used, but variable  $X_{ij}$  is relied upon.

In the second experiment, the present model proposed in the present study is compared with Jia and Routing-IP models in terms of global energy consumption as a function of the number of flows inserted into the network. The experiment parameters are summarized in Table 2.

Figure 3 plots the total energy consumption in the network according to the number of flows inserted. It may be no-

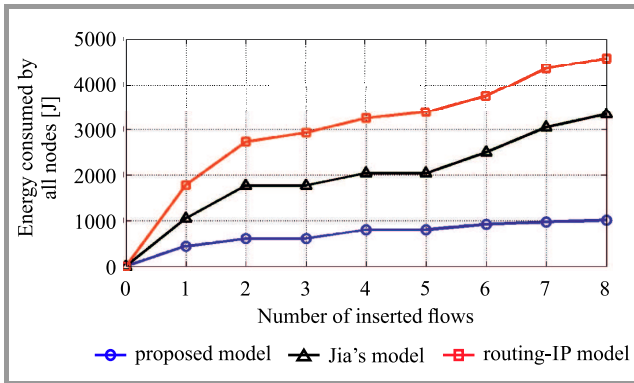


Fig. 3. Global energy consumed when the number of flows varies.

ticed that the graph associated with the proposed model is located under that related to Jia and Routing-IP models. Total energy consumption of all solutions increases along with the increase in the number of flows inserted. This is caused by the fact that when the number of flows increases, network topology must be adapted in order to route all flows while respecting QoS requirements. The latter increased the energy costs considerably. Furthermore, performance of the attained solution is better than that of two other models (Jia and Routing-IP models). On the other hand, it is also observed that the driving hypothesis is confirmed: energy consumption has been minimized, meaning that the number of unused nodes within the network has been maximized.

In the next experiment, the model proposed in the current study is compared with the Jia model in terms of the number of nodes that may be switched off, being a function of the number of flows distributed within the network. The Routing-IP model is not used in this comparison, because it is characterized by the minimum number of nodes used to route the flows.

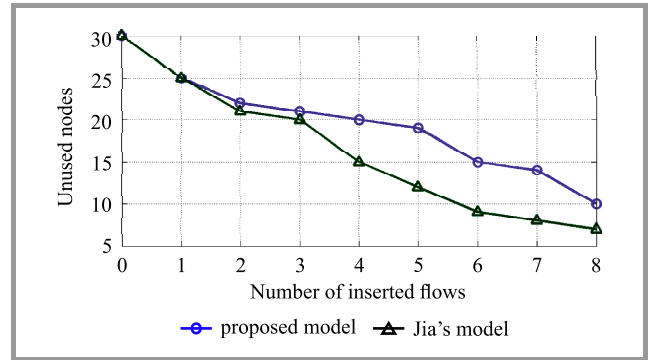


Fig. 4. Number of unused nodes when the number of flows varies.

As shown in Fig. 4, the number of unused nodes decreases along with the growing number of inserted flows. The results obtained with the use of both models match the expectations, as inserting a new flow will force its source and its destination to be activated. This means that the gains are achieved solely in relation to intermediate nodes and to the manner in which the routes pass through the nodes that are already in use. This is confirmed by the case in which

the number of inserted flows is equal to five, as shown in Table 1. From this table, it can be noticed that the number of sources and destination nodes is the same in both models, and the number of intermediate nodes in the Jia model is equal to eight, unlike the model proposed in the current study, in which it equals two only. This means that the newly proposed model, designed for the purpose of this study, is capable of turning off 75% of the intermediate nodes used in the Jia model.

## 5. Conclusion

The current study discussed the proposed solution that is based on flow aggregation instead of routing the load all over the network. Its objective was to minimize global energy consumption in ad-hoc wireless networks. The number of nodes used in the network is the main factor influencing the amount of energy consumed by these nodes globally. This is why the problem was modeled as an integer linear program with a set of linear constraints. The proposed model aims at minimizing the number of nodes used to distribute a set of flows while meeting their end-to-end QoS requirements in terms of bandwidth and delay. It is shown through simulations that the proposed model can significantly reduce the total amount of energy consumed by the network compared to other models, such as Routing-IP and Jia's.

Further research to be conducted in this area will focus on a case study in which the flows are routed more efficiently by taking into account interference, in an attempt to propose algorithms to control topology by varying the transmission energy of nodes, or to reduce the number of transmissions by coding flow packets.

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