A Green Framework for Energy Efficient Management in TDMA-based Wireless Mesh Networks

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Abstract—Due to the increasing of energy consumption in Information and Communication Technology (ICT), green computing has recently drawn a lot of attention. However, the application of green networking to Wireless Mesh Networks (WMN) has seldom been reported in the literature. In this paper, we propose a new framework for energy management in TDMA-based WMNs to support energy efficient communications. Our proposed framework aims at finding an optimal tradeoff between the achieved network throughput and energy consumption. To do so, we use resource planning through green routing and link scheduling. Specifically, we first propose an Optimal approach, called O-GRLS, by formulating the problem as an integer linear program (ILP). As this problem is known to be NP-hard, we then propose a simple yet efficient Ant Colony-based approach, called AC-GRLS to solve the formulated ILP problem. Through extensive simulations, we show that our green framework is able to achieve significant gains in terms of energy consumption as well as achieved network throughput, compared to the Shortest Path (SP) routing. Specifically, we show that the same performance as SP can be attained with minimum energy consumption. On the other hand, with the same energy cost, our proposed framework enhances the achieved throughput by up to 30% compared to SP routing.

Index Terms—Wireless Mesh Networks Management, Energy Efficient Management, Green Routing, Green Link Scheduling, Ant Colony

I. Introduction

The unprecedented expansion of broadband communication networks has led to a significant increase in energy consumption of communication networks. Indeed, the Information and Communication Technology (ICT) consumes alone 3% of world wide energy consumption, and its CO_2 emission is around 2%, which represents the same as airplanes emission and a quarter of cars emission [1]. Facing the fact that the cost of energy continues to rise, and the need for broadband supply in rural areas, green networking has become one of the most important research directions in the ICT industry. To address this challenging issue, energy efficient communication has emerged as a promising solution.

The application of green networking to Wireless Mesh Networks (WMN) has seldom been reported in the literature. Typically, a WMN [2] comprises static wireless mesh routers, also called access points (APs). Each AP serves multiple mobile users and connects them through multi-hop wireless routing to the wired network. The mesh nodes connected directly to the wired network are called gateways. They represent, respectively, the sources and sinks of downlink and uplink traffic in the WMN. Since such networks are expected to proliferate in the next few years, their energy consumption will impact the overall energy consumption of the Internet [3].

In this context and in order to build green WMNs, it is important to design energy efficient planning and management strategies. In this paper, we focus on TDMA-based WMNs (e.g., WiMax mesh networks [4]) since TDMA-based channel access facilitates the use of QoS-aware link scheduling and routing [5], [6]. We address the problem of energy efficient management from the joint routing and link scheduling stand point. Recall that a link scheduling consists in allocating to each link a set of time slots $\subset \{1, .., T\}$ on which it will transmit, where T is the scheduling period.

To this end, we propose a new green framework that provides the WMN administrator with a parameterized objective function to choose to yield the desired tradeoff between the achieved network throughput and energy consumption. Specifically, we first propose an Optimal Green Routing and Link Scheduling, called O-GRLS, that aims at finding the optimal tradeoff. In this case, we formulate the problem as an integer linear program (ILP). As this problem is known to be NP-hard [7], [8], we then propose a simple yet efficient algorithm based on Ant Colony, called Ant Colony Green Routing and Link Scheduling (AC-GRLS) to solve the formulated ILP problem. In this context, the cases of O-GRLS, a Beam Search heuristic, and Shortest Path (SP) routing strategy, are used to develop baselines to which the AC-GRLS improvements are compared. Through extensive simulations, we show that our proposed framework can achieve significant gains in terms of energy consumption as well as achieved throughput. Specifically, we show that the same performance as SP can be attained with minimum energy consumption. On the other hand, with the same energy cost, our approaches enhance the achieved network throughput. In both cases, the gains culminate at 30%.

The reminder of this paper is organized as follows. Section II presents an overview of the related works, followed by a description of the system model and the problem statement in Section III. Section IV describes our proposed framework. First, we introduce the O-GRLS method with the associated ILP formulation, then we present the AC-GRLS algorithm. Simulation results are presented in Section V. Finally, Section VI concludes this paper.

II. Related Work

Energy management has been an active research area in the last few years. Numerous proposals have been made in the literature, essentially in the context of wired networks [9]–[12]. Authors in [9] propose to reduce energy consumption in backbone networks by reducing the number of used nodes. They formulate the problem as an ILP for multi commodity flow and provide the optimal routing to reduce the number of used nodes. Authors in [10] propose to shut down nodes one by one and verify that the network still route the required traffic (i.e., the constraints are not violated). In [11], authors investigated a model based on gradient optimization to reduce energy consumption in wired networks. They started from routing paths given by a shortest path routing. Then, they used a routing policy named Energy-Aware Routing Protocol (EARP) [12] to reduce energy consumption by up to 10% given that the required QoS is satisfied.

The above schemes are not suitable for WMNs. Indeed, in such networks, the problem of interference between links is important and limits the possibility to aggregate all traffic to reuse the same nodes.

An important body of work on energy-efficiency for devices and protocols for cellular and WLAN systems has been reported in the literature. A survey on energy-efficient protocols for such networks can be found in [13]. In WLANs, authors in [14] presented strategies based on the resource on-demand concept. In [15], authors proposed an analytical model to assess the effectiveness of this concept and [16] shows management strategies for energy savings in solar powered 802.11 WMNs.

In cellular access networks, authors in [17] summarized existing energy saving approaches, which use carrier aggregation, turn off transmission components during signal-free symbols, and turn off cells during low traffic periods. Another energy management study is provided by [18], where it is shown that the on-off strategy for UMTS base station is feasible in urban areas.

In the context of WMNs, relevant works on energy-efficiency are reported in [19] and [20]. Specifically, authors in [19] consider the case of WMNs where the clients can choose the AP they connect to. To do so, they formulate and solve the problem as an ILP, where the objective is to minimize the number of used nodes (APs and gateways), while the demand is always satisfied. However, they do not take into account the interference between APs since directional antennas are assumed. In addition, they focus only on optimizing energy consumption without addressing the network throughput issue. Another energy management study in WMNs is provided in [20], where a combination between different modulation techniques and power adaptation is presented.

In our study, we focus rather on energy efficient communications by routing and scheduling the incoming traffic from APs to the mesh gateways, while considering the interference between APs, the energy consumption as well as the network throughput. Our objective is to find an optimal tradeoff between these two latter important properties. To do so, we first propose an optimization approach, by formulating the problem as an ILP, and then an Ant Colony-based approximation to solve the formulated ILP problem with low time complexity.

III. System Model

A. Network Model

We represent a WMN by a directed graph $G(V, E)$, called a connectivity graph, where $V = \{v_1, ..., v_n\}$ is the set of n nodes and E is the set of wireless links. Each node $v_i \in V$ represents an AP with a circular transmission range $R_t(i)$ and an interference range $R_I(i)$. Among the set V of all wireless nodes, some of them are gateways, which provide the connectivity to the Internet. For simplicity, let $S = \{v_{n-m+1}, ..., v_n\}$ be the set of m gateway nodes. Each node will aggregate the traffic from all its users and then route it to the Internet through some gateway node. We assume that the capacity between any gateway node to the Internet is sufficiently large.

During the transmission of the node $v_i \in V$, all the nodes residing in its transmission range receive the transmitted packet. The connectivity graph is fully defined by the connectivity matrix M; a matrix with rows and columns labeled by the graph vertices V, with a 1 or 0 in position (i, j) according to whether v_i and v_j are directly connected or not.

B. Interference Model

In this paper, we adopt the protocol interference model [21]. In this model, a node v_j is interfered by the signal from v_i whether $||v_i - v_j|| \leq R_I(i)$ and v_j is not the intended receiver. Recall that $||v_i - v_j||$ refers to the Euclidean distance between v_i and v_j.

To schedule two links at the same time slot, we must ensure that the scheduler will avoid the link interference. In other words, the transmission from v_i to v_j is viewed successful if $||v_k - v_j|| > R_I(k)$ for every node v_k transmitting in the same time slot (i.e., the receiver is interference free, as in [21]). Note that, non-interfering links can transmit in parallel during the same time slot. This model is the most restrictive among the proposed interference models in the literature [22], which means that the obtained result can be viewed as lower bounds on the achievable network throughput.

We use the conflict graph F_G to represent the interference in G. Each vertex of F_G corresponds to a directed link (i, j) in the connectivity graph G. There is a directed edge from vertex (i, j) to vertex (p, q) in F_G if and only if the transmission of link (i, j) interferes with the reception of the receiving node of link (p, q). The conflict graph F_G is then fully defined by the interference matrix I as follows:

$$I_{(i,j),(p,q)} = \begin{cases} 1 & \text{If } (p,q) \text{ interferes with } (i,j) \\ 0 & \text{Otherwise.} \end{cases}$$

C. Traffic Model

In our study, we model the traffic as a list L of flows between mesh nodes. We denote by $s(l)$ and $d(l)$ the source and destination nodes of flow $l \in L$. As the communications in WMNs are performed chiefly between the gateways and their associated APs, we consider uplink traffic (i.e., $d(l) \in S$). Note that, the traffic demands of APs represents the aggregate demands of their clients.

According to [23], the traffic demands of APs are also assumed not to change during a period of time. Indeed, in [23], the characteristics of the traffic in wireless access networks have been analyzed and it is shown that the traffic during the day can be divided into intervals of equal length. In particular,

8 intervals of 3 hours are defined [19]. It is worth noting that our model is generic and can also be used for downlink communications.

D. Problem Formulation

The general problem we are considering aims at managing mesh nodes in order to save energy when some of the network nodes are not necessary and can be switched off. The energy efficiency is, hence, calculated as being the number of nodes that could be switched off without altering the network performance. This energy saving model, called ON-OFF model, was first introduced by Restrepo et al. [24] and reused in the context of wireless networks in [25]–[29]. From an operational point of view, this can be easily integrated in centralized network management platforms commonly used for carrier grade WMNs and to the centralized and remote control of all devices and their configuration.

From energy efficiency standpoint, our work consists in determining a good tradeoff between energy consumption and achieved throughput. The problem can be described mathematically within a WMN, as follows:

GIVEN:
- A physical topology represented by the graph $G(V, E)$, which is described by the connectivity and interference matrices M and I, respectively, and a set of m gateways.
- A list L of flows originating from mesh nodes.

FIND:
- The optimal routing and link scheduling of the L flows that makes the best tradeoff between network throughput and energy consumption.

In what follows, we present our proposed framework for energy efficient management in TDMA-based WMNs.

IV. PROPOSED GREEN FRAMEWORK FOR ENERGY EFFICIENT MANAGEMENT IN TDMA-BASED WMNS

To achieve the above defined goal, we propose a new green framework based on two approaches: an Optimal one, called O-GRLS, that aims at finding the best tradeoff between the achieved network throughput and energy consumption. In this case, we formulate the problem as an integer linear program (ILP). As this problem is known to be NP-Hard [7], [8], we then propose a simple yet efficient algorithm based on Ant Colony meta-heuristic, called AC-GRLS, to solve the formulated ILP problem. A detailed description of these approaches follows.

A. O-GRLS Approach

As we consider a slotted, synchronized WMN and static topology and demands, it is reasonable to assume that the network is periodic with period T. Recall that our objective is to maximize both the total network throughput and energy saving by switching off unused nodes. The throughput is given by the ratio of successfully routed flows toward the gateways to the number of needed slots. Hence, maximizing the throughput boils down to minimizing the total number of used slots within the period T.

Let us consider the binary variable $x_{ij}^{(t)}(l)$ defined by:

$$x_{ij}^{(t)}(l) = \begin{cases} 1 & \text{If flow } l \text{ is routed from } i \text{ to } j \text{ on time slot } t \\ 0 & \text{Otherwise.} \end{cases}$$

To indicate whether an $AP_i \in V$ is ON or not, we introduce another binary variable y_i defined by:

$$y_i = \begin{cases} 0 & \text{If } \sum_{t \in [1,T]} \sum_{l \in L} \sum_{j=1}^{n} x_{ij}^{(t)}(l) + x_{ji}^{(t)}(l) = 0 \\ 1 & \text{Otherwise.} \end{cases}$$

To indicate whether a time slot t is used to transmit, we introduce the following binary variable z_t:

$$z_t = \begin{cases} 0 & \text{If } \sum_{l \in L} \sum_{i,j=1}^{n} x_{ij}^{(t)}(l) = 0 \\ 1 & \text{Otherwise.} \end{cases}$$

Our ILP can be, thus, formulated as follows:

$$Minimize\left(\alpha \sum_{i=1}^{n} y_i + (1-\alpha) \sum_{t \in [1,T]} z_t\right) \quad (1)$$

subject to:

$$x_{ij}^{(t)}(l) \leq M_{i,j} \qquad \forall i,j \in \{1,...,n\}, \forall t \in \{1,...,T\} \quad (2)$$

$$x_{ij}^{(t)}(l) + x_{pq}^{(t)}(l')I_{(i,j),(p,q)} \leq 1 \quad \forall i,j,p,q \in \{1,...,n\}, \\ \forall t \in \{1,...,T\}, \forall l,l' \in L \quad (3)$$

$$x_{ij}^{(t)}(l) = 0 \qquad \forall i \in \{n-m+1,...,n\}, j \in \{1,...,n\}, \\ \forall l \in L, \forall t \in \{1,...,T\} \quad (4)$$

$$\sum_{t=1}^{T}\sum_{j=1}^{n} x_{ji}^{(t)}(l) \leq 1, \quad \sum_{t=1}^{T}\sum_{j=1}^{n} x_{ij}^{(t)}(l) \leq 1, \forall i \in \{1,...,n\}, \forall l \in L \quad (5)$$

$$\sum_{l \in L}\sum_{t=1}^{T}\sum_{j=1}^{n} x_{ij}^{(t)}(l) = \sum_{l \in L}\sum_{t \in \{1,...,T\}}\sum_{k=1}^{n} x_{ki}^{(t)}(l) + \\ \sum_{l \in L, s(l)=i}\left(\sum_{t=1}^{T}\sum_{j=1}^{n} x_{ij}^{(t)}(l)\right) \quad \forall i \in \{1,...,n-m\} \quad (6)$$

$$\sum_{t=1}^{T}\sum_{i=1}^{n}\sum_{j=n-m+1}^{n} x_{ij}^{(t)}(l) = 1 \quad \forall l \in L \quad (7)$$

$$x_{ij}^{(t)}(l), y_i, z_t \in \{0,1\} \quad \forall i,j \in 1,...,n, \forall t \in 1,...,T \quad (8)$$

Where $\alpha \in [0,1]$ is a weighting coefficient determining the tradeoff between the achieved throughput and energy saving. For instance, assigning the value of 1 to α results in minimizing only the energy cost without taking into account the achieved throughput. Whereas, a value of 0 for α aims at focusing only on maximizing the total network throughput. Condition (2) ensures not transmitting over a non existing link. Condition (3) implies that interfering links are not scheduled to transmit in the same time slot. This constraint also restricts the capacity of a link, which means that a link is assigned to at most one flow in a given time slot t. In fact, each link is interfering with itself. Condition (4) ensures that traffic is not routed in the WMN after reaching a gateway node. This means that the gateways are assumed to have enough capacity to send all the received traffic toward the Internet. Condition (5) avoids loops while routing a flow. Condition (6) refers to the flow continuity constraint, which ensures the routed path to be continuous. It ensures that all the incoming flows are routed in addition

to the flows originating from the node. Condition (7) ensures that all the flows are successfully routed to one of the available gateways within the time period T. The last condition indicates that $x_{ij}^{(t)}(l)$, y_i and z_t are binary variables.

B. AC-GRLS Approach

The ILP formulation presented in the previous section uses link-related variables. Although this link formulation gives an optimal solution, it takes a long time to solve and thus can only be used in small-sized networks.

To reduce the above ILP resolution time, a path formulation is first introduced. In particular, the output decision variables of the above ILP will be a path for each flow instead of a link scheduled to route a flow in a given time slot. Note that path formulation scales better but at the expense of optimality. Using this path formulation, a simple yet efficient meta-heuristic based algorithm, called AC-GRLS, is proposed.

AC-GRLS is based on the Ant Colony System meta-heuristic [30], which takes inspiration from the behavior of collective ants in finding the best path between their nest and a food source. It operates iteratively (N_{max} iterations) and for each iteration the following steps are executed: 1) Formation of solutions by each ant among A_{max} ants and 2) Updating the pheromone trail. AC-GRLS algorithm is described by the pseudo-code in Algorithm 1. In the following, we detail these stages.

1) Formation of solutions :

For each flow, we consider K alternative paths toward a gateway (any of the m available gateways). A solution component will be one of the predetermined K paths. Recall that the number of possible solutions for the path formulation is $K^{|L|}$ where $|L|$ is the number of flows ($O(K^{|L|})$). The meta-heuristic guides the algorithm to explore efficiently the graph of solutions. Each ant among A_{max} ants builds the solution step by step, by adding in each step another component (i.e., a path for a flow l). The component to add is chosen according to the attractiveness of the new constructed solution (i.e., the current solution augmented by the selected component) which is called *the heuristic*, and the amount of *pheromone* deposits, which represents how this component is evaluated during the previous iterations by all ants. The *heuristic* is given by :

$$\eta = \frac{1}{\text{Objective Function Value}} \quad (9)$$

Note that, to compute the objective function value given in (1), a simple greedy link scheduling algorithm is used to schedule transmissions along all paths that form the new constructed solution. Once computed, the choice of the next component (i.e., a path j for a flow l) is selected according to a given probability. Indeed, *exploitation* is used with a probability q_0, whereas *exploration* is adopted with a probability $(1 - q_0)$.

Regarding *exploration*, the knowledge and experience of other ants is not taken into account. In this case, the next component is selected according to a probability P_{lj} given by:

$$P_{lj} = \frac{\tau_{lj}^{\alpha_{ANT}} \eta_{lj}^{\beta_{ANT}}}{\sum\limits_{k \in N_l} \tau_{lk}^{\alpha_{ANT}} \eta_{lk}^{\beta_{ANT}}}$$

Algorithm 1 AC-GRLS algorithm

IN: Set of flows, K alternative paths for each flow
OUT: A routing solution (One path for each flow)
Set Parameters: q_0, α_{ANT}, β_{ANT}, Q
Initialize pheromone trails and best_solution
for $nb = 1 \rightarrow$ Number of Iterations **do**
  //Construct Ant Solutions
  for all ant in A_{max} **do**
    current_solution $\leftarrow \{\}$
    for $l = 1 \rightarrow$ Number of flows **do**
      $p \leftarrow Random(0..1)$
      if $p < q_0$ **then**
        Choose path j where
        $j = \text{Argmax}_{k \in N_l} \left(\tau_{lk}^{\alpha_{ANT}} \times \eta_{lk}^{\beta_{ANT}} \right)$
      else
        Choose path j according to P_{lj} probability
        $P_{lj} = \frac{\tau_{lj}^{\alpha_{ANT}} \eta_{lj}^{\beta_{ANT}}}{\sum\limits_{k \in N_i} \tau_{lk}^{\alpha_{ANT}} \eta_{lk}^{\beta_{ANT}}}$
      end if
      Add the jth path for flow l to current_solution
    end for
    if current_solution is better than best_solution **then**
      best_solution $\leftarrow$ current_solution
    end if
  end for
  //Update Pheromones for all flows l
  $\tau_{lj} \leftarrow (1 - \rho)\tau_{lj}$ //Evaporate all pheromones
  if current_solution is the best solution for the current iteration And j^{th} path is selected for flow l **then**
    $\tau_{lj} \leftarrow \tau_{lj} + \Delta_{lj}^{best}$
  end if
end for
Return best_solution

Where N_l is the set of all possible paths for the solution component l (i.e., $|N_l| = K$), η_{lj} and τ_{lj} denote, respectively, the heuristic value given in equation (9), and the pheromone trail of the jth path for flow l, and α_{ANT} and β_{ANT} determine, respectively, the relative importance of τ_{lj} and n_{lj}.

On the other hand, in *exploitation*, the experience of the other ants is used. Indeed, among the possible components to add, the one with the highest value of $\tau_{lj}^{\alpha_{ANT}} \times \eta_{lj}^{\beta_{ANT}}$ is selected.

The criterion to choose the best solution is the objective function given in equation (1).

2) Pheromone trail update:

At the end of each iteration, the pheromones (trail values) for each flow l are updated as follows:
$$\tau_{lj} = (1 - \rho)\tau_{lj} + \Delta_{lj}^{best}$$
where ρ is the decay coefficient of the pheromone, $\Delta_{lj}^{best} = Q/\eta^{best}$ if flow l is routed through the jth path in the best solution of the current iteration, 0 otherwise, and Q is a constant called the *pheromone update constant*. Recall that $\eta^{best} = 1/Objective\ function\ value\ of\ the\ best\ solution$, as reported in equation (9).

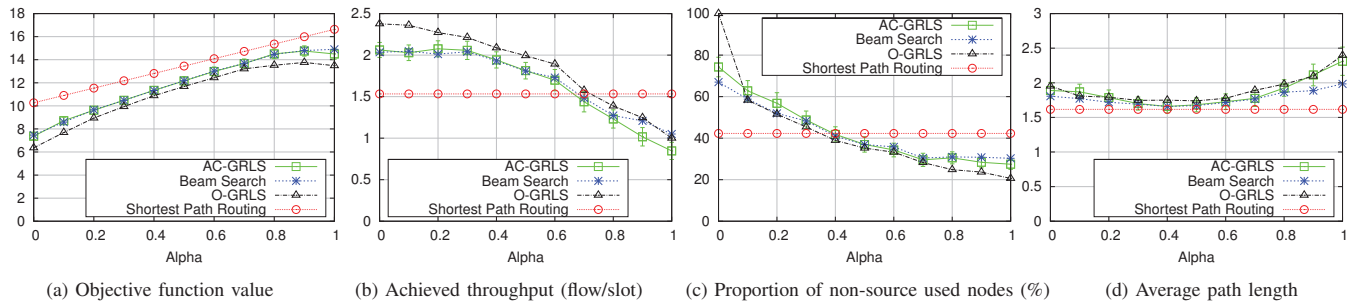Note that the complexity of AC-GRLS is given by $O(N_{max} \times A_{max} \times |L| \times K)$.

| (a) Objective function value | (b) Achieved throughput (flow/slot) | (c) Proportion of non-source used nodes (%) | (d) Average path length |

Fig. 1. Comparison of the results for O-GRLS, AC-GRLS, Beam Search and SP routing with a topology of 25 nodes, 4 gateways and 75% network load

V. PERFORMANCE EVALUATION

In this section, we evaluate the efficiency of our proposed green framework. Specifically, we study the gain that both O-GRLS and AC-GRLS introduce compared to the Shortest Path (SP) routing and Beam Search algorithms, under various network load and densities.

The analysis is based on random and grid topologies. For lack of space, we provide in this analysis some of the obtained results related to grid topologies. We consider different network sizes: 25 (5 x 5) APs with 4 gateways (located at the 4 corners of the grid), and 100 (10 x 10) APs with 9 gateways, which are representative of small and large-sized WMNs, respectively. Then, based on the transmission range R_t and the interference range $R_I = 1.5 \times R_t$, both the connectivity and conflict graphs are derived. In our simulations, we considered different traffic loads: 25%, 50%, and 75% to show the impact of network load on the evaluated metrics. The traffic sources are chosen randomly among the $(n-m)$ APs. Recall that n and m denote, respectively, the total number of APs and gateways in the WMN. In addition, we vary the weighting coefficient α to determine the good tradeoff between energy consumption and throughput.

The performance metrics used in our simulations concern the computation time, the objective function value given in equation (1), the proportion of non-source used nodes (i.e., relay nodes and gateways that are active), which reflects the energy cost used to forward the required L flows, and the achieved throughput. Other additional metrics the average path length are also investigated. Note that in our analysis, only gateways and relay non-source APs can be switched off, since the source nodes are assumed to be always active.

The reported results are obtained using the solver *ILOG CPLEX* [31] for O-GRLS and a Java^{TM} implementation for AC-GRLS, SP, and Beam Search. Our simulations are run until a narrow 95% confidence interval is achieved. Table I reports the simulation parameters used for AC-GRLS. Note that these parameters are set experimentally by tuning them to find good values.

First, we study the computation time needed for all methods to solve the green joint routing and link scheduling problem. As reported in Table II, we can see that AC-GRLS takes a very short time (up to 5 seconds in the small-sized WMN case, and up to 10 seconds in the large-sized case), compared to both Beam Search and O-GRLS, which can reach 600 seconds. The SP algorithm, on the other hand, needs less than 1 second (in

TABLE I
AC-GRLS SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
α_{ANT}	0.1	ρ	0.2
β_{ANT}	1.1	Number of Ants	6
Q	$|L|$	Number of iterations	10
q_0	0.1		

the 25 APs case) since no energy saving is considered. This is actually what a link-state routing protocol does. Note that these measurements are performed on a PC with 2.4 GHz of CPU and 4.00 GB of RAM.

Let us now focus on the comparison among the different strategies based on the energy cost and achieved network throughput.

Fig. 1 shows mainly the objective function value, the energy cost and the achieved throughput for the 25-AP grid topology network case and when 75% of the network load is used. We can observe that the mean values of the objective function obtained for O-GRLS fit or are very close to the confidence intervals of AC-GRLS (see Fig. 1a). This means that AC-GRLS can converge to the optimal solution within a short time period, as reported in Table II. Furthermore, We can also observe that we succeed to reduce the objective function value by up to 30% using AC-GRLS compared to the SP routing strategy. Note that the Beam Search also gives acceptable values, but this comes at the expense of high computation time, as reported in Table II. We can see that the energy cost and the achieved throughput decrease with the increase of α for all strategies, except for the SP algorithm since this latter does not take into account energy consumption. When $\alpha = 1$, the consumed energy is set to minimum but at the expense of low achieved throughput. It is worth noting that, since AC-GRLS, Beam Search and SP use a simple greedy link scheduling, the achieved throughput can be viewed as a lower bound of the possible achieved one when using other "advanced" link scheduling algorithms.

The main observation regarding Fig.1 is when $\alpha \in [0.4, 0.7]$. Indeed, within this range, our proposed algorithms achieve better throughput than the SP strategy (see Fig. 1b), and at the same time consume less energy, since they use a reduced number of relaying nodes (see Fig. 1c). The rational behind this is that, from an operator point of view, a good resource planning is reached when α is parameterized within this range. As such, both the network performance and the energy saving will be improved. In particular, for $\alpha = 0.7$, an operator succeeds in achieving the same performance as SP by

TABLE II

Network Size	Network Load	O-GRLS	AC-GRLS	Beam Search	Shortest Path
25 nodes	25%	246.61±26.31	0.35±0.47	0.03±0.14	0.02±0.02
4 gateways	50%	501.91±19.53	1.75±2.19	0.65±1.14	0.35±0.10
	75%	598.11±12.51	5.06±6.69	26.58±65.74	0.73±0.15
100 nodes	25%	-	8.42±2.4	44.67±3.19	0.31±0.13
9 gateways	50%	-	9.15±3.7	81.20±15.14	5.76±3.10
	75%	-	10.6±4.1	132.58±65.74	1.73±0.15

(a) Objective function value (b) Achieved throughput (flow/slot) (c) Proportion of non-source used nodes (%) (d) Average path length
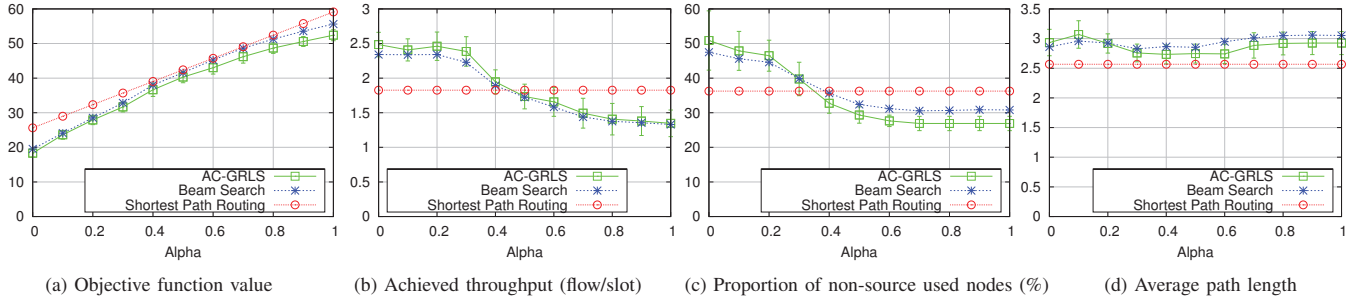
Fig. 2. Comparison of the results for AC-GRLS, Beam Search and SP routing with a topology of 100 nodes, 9 gateways and 50% network load

consuming less energy. In this case, the energy saving is about 29%. Whereas, for $\alpha = 0.4$, the network consumes the same energy as SP, but at the same time achieves a higher network throughput. The gain culminates at 30% in this case.

Another important usage of the above results is the selection of the best value of α to guarantee a certain network throughput, while reducing the total energy cost. This could be used by the WMN administrator to seek a desired tradeoff. For instance, if one wants to achieve, at least, a throughput of 1.75 $flow/slot$, a value of $\alpha = 0.5$ could be selected if our AC-GRLS approach is adopted.

Finally, the average path length for all strategies is depicted in Fig. 1d. As expected, the SP algorithm selects paths with minimum number of hops toward the gateways. However, our approaches (i.e., O-GRLS and AC-GRLS) also select paths that have the tendency to be short too, in particular when α is within the range $[0.3, 0.7]$. Indeed, as shown in Fig. 1d, when $\alpha = 0.4$ (i.e., same energy cost), the average path length is almost the same as SP. This means that our approaches can achieve high network throughput without increasing the average path length as well as energy cost. This results in efficient end-to-end delay, since the path length impacts the delay a flow may experience in the network. On the other hand, when $\alpha = 0.7$ (i.e, low energy cost), the average path length is slightly higher than with SP. This shows that even though our approaches use slightly longer paths than SP, the energy cost is not affected since the flows are routed through already active nodes, thus enabling green networking.

Last but not least, to show the scalability of our AC-GRLS approach, we carried out additional simulations in large-sized networks. The results are presented in Fig. 2 where the same observation can be made. Indeed, we can see that for $\alpha = 0.45$, the same throughput as SP is achieved, while using less nodes. The energy saving is about 20%, as shown in Fig. 2c. However, with the same energy cost, better throughput is achievable with AC-GRLS for $\alpha = 0.35$, and the gain can attain 22%, as

shown in Fig. 2b. Note that, results regarding O-GRLS are not provided due to the inherently high computation time.

It is worth noting that comparable results have been obtained in the case of random networks of the same sizes. Indeed, the energy saving is about 20% for both small and large-sized networks. While the achievable network throughput improvement is about 28% for small-sized networks, and 20% for large-sized ones.

VI. CONCLUSION

In this paper, we investigated the energy management problem in TDMA-based WMNs. We proposed a new green framework for energy efficient communications based on two approaches: an Optimal one, called O-GRLS, and an Ant Colony-based one, called AC-GRLS. Both approaches allow to tune and find a good tradeoff between the achieved network throughput and energy consumption using a parameterized objective function. The latter provides network administrators with a mean to find the best network throughput for a given energy budget and vice-versa. Through extensive simulations, we showed how our framework can achieve significant gains in terms of energy consumption as well as achieved nework throughput, compared to the Shortest Path (SP) routing, as well as the Beam Search heuristic. Specifically, in small-sized networks, for grid and random networks, our energy management approaches can save, respectively, 29% and 20% of the energy cost, while achieving the same performance as SP. However, if the network consumes the same energy as SP, the achieved throughput can be enhanced by up to 30%. These gains are maintained in large-sized networks. Indeed, we showed that the energy saving is about 20%, while the achievable throughput improvement is about 20% for both grid and random network topologies. In addition, we showed that AC-GRLS converges to the optimal solution in small-sized WMNs and has low computation time in large-sized ones, which makes it a feasible and efficient solution for green WMNs and energy efficient management.

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