

Online Flow-based Energy Efficient Management in Wireless Mesh Networks

Ahmed Amokrane*, Rami Langar*, Raouf Boutaba^{†‡}, Guy Pujolle^{*‡}

*LIP6 / UPMC - University of Paris 6; 4 Place Jussieu, 75005 Paris, France

[†]School of Computer Science, University of Waterloo; 200 University Ave. W., Waterloo, ON, Canada

[‡]POSTECH, 77 Cheongam-Ro, Nam-Gu, Pohang, Gyeongbuk, Korea

Email: ahmed.amokrane@lip6.fr; rami.langar@lip6.fr; rboutaba@uwaterloo.ca; guy.pujolle@lip6.fr

Abstract—The last few years have witnessed an increase in energy consumption in Information and Communication Technology (ICT). Naturally, energy efficient solutions are becoming crucial for both local and wireless access networks. In this paper, we propose a new framework to support energy efficient management in Wireless Mesh Networks (WMNs). A key distinguishing feature of our solution is its online flow-based routing approach since existing flows are dynamically consolidated or even re-routed at fixed intervals according to live arrival and departure of mesh clients. The proposed solution is compliant with emerging Software Defined Networking (SDN) paradigm since it relies on a central controller to monitor and manage the network.

To achieve this, we first formulate the problem as an integer linear program (ILP). As this problem is known to be \mathcal{NP} -hard, we then propose a simple yet efficient Ant Colony-based approach to solve the formulated ILP problem. Through extensive simulations, we show that our proposed approach is able to achieve significant gains in terms of energy consumption, compared to conventional routing solutions such as the Shortest Path (SP) routing, the Minimum link Residual Capacity routing metric (MRC) and the load balancing (LB) scheme. Specifically, we show that our approach reduces the energy consumption by up to 13%, 20%, and 52%, compared to MRC, SP and LB, respectively, while achieving the required QoS.

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 CO₂ emission is around 2%, which represents the same as airplanes emission [1]. Access networks account for 10% of this amount. To address this challenging issue, energy efficient communications has emerged as a promising solution.

The application of green networking to Wireless Mesh Networks (WMNs) has seldom been reported in the literature. Typically, a WMN [2] comprises static wireless mesh routers, also called Mesh Access Points (MAPs). Each MAP 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 (i.e., connecting the WMN to the wired network) are called gateways.

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, it is important to design energy efficient planning and management strategies that take into account the dynamic and unpredictable users' mobility.

Recently, Software Defined Network (SDN) [4] has emerged as a solution for network management. The key idea behind

SDN is to move the forwarding intelligence into a central network controller, while keeping the routers or switches simple. This allows to implement different forwarding approaches efficiently. In SDN, the controller dictates the forwarding rules of flows to the forwarding elements using protocols such as OpenFlow [5]. A preliminary solutions based on OpenFlow for WMNs has been proposed in [6].

Motivated by the new SDN paradigm, we propose in this paper an online flow-based routing in WMNs. Our objective is to minimize the energy consumption of MAPs over time, while routing incoming flows subject to QoS constraints (such as bandwidth and delay) and taking into account the dynamic and unpredictable arrival, departure and mobility of mesh clients. Our proposed approach can be easily integrated in an SDN solution since it relies on a central controller that monitors and manages the network and decides on flow routes.

To achieve this, we first formulate the problem as an integer linear program (ILP). The formulated objective function takes into account the costs for switching between sleeping and active modes of MAPs, as well as re-routing or consolidating existing flows. As this problem is known to be \mathcal{NP} -hard [7], we then propose a simple yet efficient algorithm based on Ant Colony, called Ant Colony Online Flow-based Energy efficient Routing (AC-OFER) to solve the formulated ILP problem. In this context, Shortest Path (SP) routing strategy, the Minimum link Residual Capacity routing metric (MRC) and the Load Balancing (LB) approaches are used to develop baselines to which the AC-OFER improvements are compared. Through extensive simulations, we show that our proposed approach can achieve significant gains in terms of energy consumption. Specifically, the gains can attain 13%, 20% and 52% compared to MRC, SP and LB, respectively, for large-sized networks and medium traffic load, while achieving the same client requests acceptance ratio and required QoS.

The reminder of this paper is organized as follows. Section II presents an overview of the related work. In Section III, we describe the system model used in our analysis. Section IV formulates the problem as an ILP, followed by a presentation of our proposal in Section V. Simulation results are presented in Section VI. Finally, Section VII concludes this paper.

II. RELATED WORK

Energy management has been an active research area in the last few years. An important body of work on energy-efficiency for devices and protocols for cellular, WLAN systems and Wireless Sensor Networks (WSNs) has been reported in the

literature. A survey on energy-efficient protocols for such networks can be found in [8]. In WLANs, authors in [9] presented strategies based on the resource on-demand concept. In [10], authors proposed an analytical model to assess the effectiveness of this concept and [11] shows management strategies for energy savings in solar powered 802.11 WMNs. In cellular access networks, authors in [12] 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. In WSNs, the energy expenditure in a node is typically dominated by the transmission unit. From the energy efficiency standpoint, the most effective solution is to put the wireless nodes in sleep mode [13]. Our proposed approach takes into account the sleep consumption mode, but unlike WSNs, where the objective is to load-balance the energy expenditure across nodes to extend the network's lifetime, our objective is to calculate the minimum number of active MAPs required to forward the traffic in order to minimize the overall energy consumption.

In the context of WMNs, relevant works on energy-efficiency are reported in [14]–[18]. These works consider offline routing in such networks. Specifically, authors in [14] consider the case of WMNs, where the clients can choose the MAP 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 (i.e., MAPs and gateways), and always satisfy clients' bandwidth demands. However, they do not take into account the interference between MAPs since directional antennas are assumed. The authors extended this work in [15] to consider the planning and deployment of MAPs (i.e., choosing the number of MAPs and their location). Another energy management study in WMNs is provided in [16], where a combination between different modulation techniques and power adaptation is presented. In our previous work [17], we proposed a framework for energy efficient management in TDMA-based WMNs. However, all the aforementioned approaches are still limited since they are offline. Indeed, the traffic patterns are assumed to be known a priori at the planning stage, which is not usually the case in practice. This may limit the utilization of such approaches in real world deployment.

Considering battery supplied WMNs, Chen et. al, [18] proposed a cross-layer solution that adjusts sleep periods of MAPs. However, this approach considers MAPs that use batteries and the routing decisions are made based on the remaining energy along the paths. In our study, we consider instead power line supplied MAPs, which makes the routing decisions follow the paths with minimum energy consumption and not maximum remaining energy of nodes.

General insights on how energy efficient could be achieved in WMNs were introduced in [3], such as switching off nodes, transmission power control, rate adaptation and on/off cycle duration adjustment for MAPs. However, no details on how effective such techniques could be are given.

In [6], the authors present an open flow-based approach for efficient mobility management in WMNs using the SDN concept.

Adopting the same SDN paradigm as in [6], in this paper, we propose an online flow-based routing approach in WMNs. However, we focus rather on energy efficient communications by routing the incoming traffic from clients to the mesh

gateways, while considering the required QoS, the energy consumption as well as the costs of flows reconfiguration and re-routing. To the best of our knowledge, this work is the first to address online flow-based management and dynamic reconfiguration over time for energy efficient routing in WMNs. To achieve this, we first propose an optimization approach, by formulating the problem as an ILP, and then present 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 is the set of n nodes and E is the set of wireless links. Each node $v \in V$ represents a MAP. Some of them are gateways, which provide connectivity to the Internet. For simplicity, let S be the set of gateway nodes. A wireless link e between two MAPs has a number of channels denoted by nc_e . The capacity along each channel is limited and denoted by C_{ek} . Similarly, each MAP $i \in V$ has a limited capacity to service its attached clients denoted by C_i , whereas each gateway $j \in S$ has, in addition to that, a limited capacity for traffic forwarding towards the Internet denoted by G_j .

B. Energy Consumption Model

First of all, recall that a MAP $v \in V \setminus S$ has two physical interfaces: one for serving its mesh clients (called AP interface) and one for relaying traffic in the WMN backbone towards the gateways (called mesh interface). An additional third wired interface exists for gateway nodes (i.e., MAP $v \in S$) to forward traffic to/from the Internet.

Given a MAP $v \in V$, we distinguish between two operating modes: one with low power consumption and one with high power consumption. In the first mode, a MAP has no clients attached to it and no traffic to forward. In this case, it only uses its AP Interface to detect users' presence. In this mode, the energy consumption of the MAP can be reduced by setting up a high sleeping period and reducing the transmission power [3]. In the second mode, the MAP has either active clients attached to it or traffic to forward. Therefore, its power consumption is higher. Consequently, six power consumption profiles for a MAP $v \in V$ can be defined and are listed in the following:

- P_R : If v is used as a mesh router only. This means that v has traffic to forward but does not have clients attached to it.
- P_{AG} : If v is used as an access point and a gateway at the same time. This means that v acts as a gateway and has active clients attached to it.
- P_{AR} : If v is used as an access point and a mesh router at the same time. This means that v has active users attached to it and uses its mesh interface to forward traffic.
- P_{RG} : If v is used as a mesh router and gateway at the same time.
- P_{ARG} : If v is used as an access point, a mesh router and a gateway at the same time. In this case, v uses its three interfaces at the same time. This is the most power hungry profile.
- P_S : If v has no active clients attached to it, no traffic to forward and is not used as a gateway. This is the power

saving mode of a MAP. Note that P_S could be negligible compared to the other profiles.

To reduce energy consumption of the whole network, one should put as many nodes as possible into power saving mode and optimize the power consumption over the remaining nodes.

C. Traffic Model

In this work, we model the traffic as a set of L flows. Each flow originates from a mesh client. The clients are located in the coverage area of one or multiple MAPs, which is captured by the coverage matrix A . Each flow $l \in L$ has a bandwidth demand b_l and a delay constraint d_l . In our study, we assume a multichannel WMN, where interfering wireless links operate on different channels, thus enabling multiple parallel transmissions. In such multi-hop network, we assume the delay to be proportional to the number of hops between the serving MAP and the gateway. The delay constraint d_l is thus translated into an upper bound on the number of allowed hops. Without loss of generality, we assume that the traffic is uplink. This means that each originated flow must be routed towards a gateway.

IV. PROBLEM FORMULATION

As already mentioned, our objective is to minimize the energy consumption of MAPs over time, while routing dynamically the arriving and leaving flows subject to QoS constraints (i.e., bandwidth and delay). More specifically, the problem could be formulated 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.
- A set of m gateways in the WMN.
- A set L of flows originating from clients, each one with its bandwidth demand b_l and delay constraint d_l .
- The coverage matrix A of MAPs.
- The previous attachment of clients and their flows' routes

FIND:

- The optimal attachment of each user to one of the covering MAPs and the optimal routing of its corresponding flow that minimizes the network operation and reconfiguration costs, subject to QoS constraints (i.e., bandwidth and delay).

ILP Formulation

In the following, we formulate the flow-based routing problem as an integer linear program (ILP). For ease of understanding, table I summarizes the symbols used in our analysis.

Let t be the epoch starting when one of the following events occurs: client arrival/departure or user movement between two MAPs. We denote by $t - 1$ the epoch before t . For the sake of presentation, let use the notation y and y' to designate the state of the variable y at epoch t and $t - 1$, respectively.

We introduce the binary variable w_{li} to indicate whether the client originating the flow l is attached to the MAP $i \in V$ or not. To represent the link and channel allocation, we define another binary variable $f_{e,k,l}$, which takes the value of 1 whenever the flow l uses the channel k on link e on its route.

TABLE I
TABLE OF NOTATIONS

Notation	Meaning
$f_{e,k,l}$	0 or 1, whether the channel k of a link e is used to route the flow l
y_i	0 or 1, whether a MAP is in the active or sleep mode
y_i^+	0 or 1, whether a MAP is turned into the active mode
y_i^-	0 or 1, whether a MAP is turned into the sleep mode
r_{il}^+	0 or 1, whether a MAP i is added to the path of flow l
r_{il}^-	0 or 1, whether a MAP i is removed from the path of flow l
cs_i^+	Cost of turning a MAP into the active mode
cs_i^-	Cost of switching a MAP into the active mode
cr_{il}^+	Cost of rerouting a flow l by adding node i to its path
cr_{il}^-	Cost of rerouting a flow l by removing node i from its path
nc_e	Number of channels of link e
C_{ek}	Capacity of channel k of link e
C_i	Capacity of MAP i
G_j	Capacity of gateway j
w_{li}	0 or 1, whether a the client source of flow l is attached to MAP i

To indicate whether a MAP $i \in V$ is used or not, we introduce another binary variable y_i defined by:

$$y_i = \begin{cases} 0 & \text{If } \sum_{l \in L} \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} + \sum_{l \in L} w_{li} = 0 \\ & i \in \{s(e), d(e)\} \\ 1 & \text{Otherwise.} \end{cases}$$

Where $s(e)$ and $d(e)$ respectively denote the source and destination of wireless link $e \in E$.

Let consider the variable y_i^+ and y_i^- that represent, respectively, the decision of switching a MAP i to active mode or sleep mode, at network reconfiguration. They are defined as follows:

$$y_i^+ = \begin{cases} 1 & \text{if } y_i' = 0 \text{ and } y_i = 1 \\ 0 & \text{Otherwise.} \end{cases}$$

$$y_i^- = \begin{cases} 1 & \text{if } y_i' = 1 \text{ and } y_i = 0 \\ 0 & \text{Otherwise.} \end{cases}$$

Note that switching a node from a sleep mode to active mode and vice versa generates a cost. This cost is denoted by cs_i^+ and cs_i^- , respectively, and could be the time needed to turn on the node or the energy that is consumed to set up the routing tables (e.g., flow table). In addition, we assume that there is a cost for re-routing a flow to a more favorable route. Hence, let consider the variables r_{il}^+ and r_{il}^- representing, respectively, whether a flow l is re-routed through node i , after network reconfiguration, or removed from being routed through node i . They are defined as follows:

$$r_{il}^+ = \begin{cases} 1 & \text{If } \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l}^- = 0 \\ & i \in \{s(e), d(e)\} \\ \text{and } \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \geq 1 \\ & i \in \{s(e), d(e)\} \\ 0 & \text{Otherwise.} \end{cases}$$

$$r_{il}^- = \begin{cases} 1 & \text{If } \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l}^- \geq 1 \\ & \text{and } \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} = 0 \\ & \text{and } i \in \{s(e), d(e)\} \\ 0 & \text{Otherwise.} \end{cases}$$

The re-routing costs will be thus represented by cr_{il}^+ and cr_{il}^- , respectively.

Finally, the power consumption of a MAP is given by P_i as follows:

$$P_i = \begin{cases} P_R & \text{If } \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \geq 1 \text{ and } \sum_{l \in L} w_{li} = 0 \\ & \text{and } i \in \{s(e), d(e)\} \\ & \text{and } i \notin S \\ P_{AR} & \text{If } \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \geq 1 \text{ and } \sum_{l \in L} w_{li} \geq 1 \\ & \text{and } i \in \{s(e), d(e)\} \\ & \text{and } i \notin S \\ P_{AG} & \text{If } \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} = 0 \text{ and } \sum_{l \in L} w_{li} \geq 1 \\ & \text{and } i \in S \\ P_{RG} & \text{If } \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \geq 1 \text{ and } \sum_{l \in L} w_{li} = 0 \\ & \text{and } i \in S \\ P_{ARG} & \text{If } \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \geq 1 \text{ and } \sum_{l \in L} w_{li} \geq 1 \\ & \text{and } i \in S \\ 0 & \text{Otherwise.} \end{cases}$$

We now formulate the problem of routing the new incoming flow and dynamically re-optimizing the existing flows as an ILP with the following objective function:

$$\text{Minimize} \left(\alpha_E \sum_{i \in V} P_i + \alpha_S \sum_{i \in V} (y_i^+ cs_i^+ + y_i^- cs_i^-) + \alpha_R \sum_{i \in V} \sum_{l \in L} (r_{il}^+ cr_{il}^+ + r_{il}^- cr_{il}^-) \right) \quad (1)$$

Where, α_E , α_S and α_R respectively represent weight factors that achieve a tradeoff between power consumption, re-routing flows and switching nodes to different states. They might represent the cost in dollar (e.g., cost of electricity for α_E). Note that the first term in the objective function is related to the energy consumption when using a node i . The second term corresponds to the cost of switching nodes from sleeping/active states after reconfiguration, and the third term captures the cost of re-routing flows.

The optimization is subject to the following constraints (2)-(11):

- Not exceeding the capacities of links and channels:

$$\sum_{l \in L} f_{e,k,l} \times b_l \leq C_{ek}, \forall e \in E, \forall k \in \{1, \dots, nc_e\} \quad (2)$$

- Not exceeding gateway capacities:

$$\sum_{l \in L} \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \times b_l + \sum_{l \in L} w_{li} \times b_l \leq G_i \quad \forall e \in E, d(e) = i \text{ and } i \in S \quad (3)$$

- Not exceeding the MAPs capacities:

$$\sum_{l \in L} w_{li} \times b_l \leq C_i \quad \forall i \in V \quad (4)$$

- A client can attach to, at most, one MAP that covers its location:

$$\sum_{i \in V} w_{li} \leq A_{li}, \quad \forall l \in L \quad (5)$$

- The delay constraint of a flow l should be satisfied:

$$\sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \leq d_l, \quad \forall l \in L \quad (6)$$

- A flow is not routed when it reaches a gateway unless the gateway capacity is exceeded, in which case the traffic is forwarded to another gateway:

$$\sum_{l \in L} \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \times b_l + \sum_{l \in L} w_{li} \times b_l \leq G_i + \sum_{l \in L} \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \times b_l, \quad \forall i \in S \quad (7)$$

- No loops when routing. This means that a flow comes in or goes out from a node at most once. Hence, we have:

$$\sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \leq 1, \quad \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \leq 1, \quad \forall i \in V, \forall l \in L \quad (8)$$

- Flow conservation constraint, which ensures that the network flow that enters a node plus the traffic originating from this node is equal to the outgoing traffic from this node. It can be written as follows:

$$\sum_{l \in L} \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \times b_l = \sum_{l \in L} \sum_{e \in E} \sum_{k=1}^{nc_e} f_{e,k,l} \times b_l + \sum_{l \in L} w_{li} \times b_l, \quad \forall i \in V \setminus S \quad (9)$$

- Two links that interfere with each other cannot transmit at the same time. This means that the sum of their proportion of link usage should not exceed 1.

$$\sum_{l \in L} \frac{f_{e,k,l} \times b_l}{C_{ek}} + \sum_{l' \in L} \sum_{e' \in E} \frac{f_{e',l',k} \times b_{l'} \times I_{(e,k),(e',k)}}{C_{e'k}} \leq 1 \quad \forall e \in E, \forall k \in \{1, \dots, nc_e\} \quad (10)$$

- The decision variables are binary

$$f_{e,k,l}, w_{li} \in \{0, 1\}, \quad \forall i \in V, \forall e \in E, \forall l \in L \quad (11)$$

V. AC-OFER PROPOSAL

The formulated ILP problem presented in Section IV is assumed to be solved by the network controller each epoch t (i.e., each incoming flow). Clearly, such approach is not feasible in practice, since it generates high overhead due to the frequent updates of the flow tables. In addition, the above ILP problem is \mathcal{NP} -hard [7].

To overcome this limitation, we propose here a simple yet efficient meta-heuristic algorithm, called AC-OFER, which is executed at each pre-defined time period T (and not at each incoming flow). The benefit of doing so is twofold: (i) to reduce the overhead and (ii) to decide on flow re-routing that optimizes the overall energy consumption of the network. We call this step “*Dynamic Network Reconfiguration*”. On the other hand, each incoming flow within the time frame T will be injected in the network without incurring any change on the already established routes of existing flows. This step is referred to as “*Network Event Handling*”. In the following, we detail these two steps.

A. Network Event Handling

On detecting the “user arrival” event, one or multiple served MAPs first send the corresponding flow QoS requirements (i.e., bandwidth and delay constraints) to the network controller using a virtual control interface. In fact, as proposed and validated in [6], each physical wireless interface can be split into two virtual interfaces. One virtual interface is used for control traffic and the other one for data traffic.

Since no dynamic reconfiguration is performed at this level, the network controller chooses, among the possible paths, the one with the minimum score given by the objective function in (1), without incurring any change on existing flow routes. In this case, virtual data interfaces are used to forward traffic along the selected path between the served MAP and the selected gateway. Note that in case of client exit, its corresponding flow will be removed from the network and the used resources will be released.

B. Dynamic reconfiguration using Ant Colony Online Flow-based Energy efficient Routing (AC-OFER)

To optimize the overall energy consumption and for better resource usage, the network controller needs to reconfigure the flow routes in the network. This is achieved at each predefined time period T . To this end, we propose to approximate the optimal solution of the said ILP using an Ant Colony-based approach, called AC-OFER, described by the pseudo-code in Algorithm 1. AC-OFER operates iteratively with N_{max} iterations. 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.

1) Formation of solutions :

For each flow $l \in L$, we consider K alternative paths towards any of the gateways. A solution component will be one of the predetermined K paths. 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) starting by flows with the highest bandwidth demand. The component to add is chosen according to the attractiveness of the new

Algorithm 1 AC-OFER algorithm

IN: WMN with routed flows (i.e., previous routes solution)
OUT: A new routes solution (One path for each flow)
Set Parameters: $q_0, \alpha_A, \beta_A, Q$
Initialize pheromone trails and best_solution to the previous 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**
 $p \leftarrow \text{Random}(0..1)$
 if $p < q_0$ **then**
 Choose path j among the K paths where
 $j = \text{Argmax}_{k \in N_l} (\tau_{lk}^{\alpha_A} \times \eta_{lk}^{\beta_A})$
 else
 Choose path j according to P_{lj} given in (13)
 end if
 Add the j^{th} 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

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 :

$$\eta = \frac{1}{\text{Objective Function Value given in (1)}} \quad (12)$$

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 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:

$$P_{lj} = \frac{\tau_{lj}^{\alpha_A} \eta_{lj}^{\beta_A}}{\sum_{k \in N_l} \tau_{lk}^{\alpha_A} \eta_{lk}^{\beta_A}} \quad (13)$$

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 (12), and the pheromone trail of the j^{th} path for flow l , α_A and β_A determine, the relative importance of τ_{lj} and η_{lj} , respectively.

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 $\tau_{lj}^{\alpha_A} \times \eta_{lj}^{\beta_A}$ is selected.

2) Pheromone trail update:

At the end of each iteration, the solution with the lowest score of the objective function given in (1) is chosen as the best

TABLE II
AC-GRLS SIMULATION PARAMETERS

Parameter	Value	Parameter	Value	Parameter	Value
α_A	0.12	ρ	0.2	P_{AG}	18 W
β_A	1.1	A_{max}	5	P_{RG}	18 W
Q	$ L $	N_{max}	8	P_{ARG}	20 W
q_0	0.1	P_R	15 W	P_S	3 W
T	30 minutes	P_{AR}	16 W		

solution for this iteration. Then, 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 j^{th} path in the best solution of the current iteration, 0 otherwise, and Q is a constant called the *pheromone update constant*.

VI. PERFORMANCE EVALUATION

In this section, we evaluate the efficiency of our proposed approach. Specifically, we study the gain that AC-OFFER introduces compared to the Shortest Path (SP) routing, the Minimum link Residual Capacity (MRC) routing metric proposed in [19] and the Load Balancing (LB) scheme, under various network load and densities. Note that the aim of MRC is to group the traffic through same paths in order to reduce the number of used nodes, whereas LB is used to illustrate the worst case power consumption scenario. To this end, we developed our own discrete event simulator in *Java*.

The analysis is based on random and grid topologies. Due to space limitation, we present results only for grid-based WMN topologies. We consider different network sizes: 25 (5 x 5) MAPs with 3 random gateways, 49 (7 x 7) MAPs with 7 gateways and 100 (10 x 10) MAPs with 9 gateways, which are representative of small, medium and large-sized WMNs, respectively. The interference range R_I is set to $1.5 \times R_t$, where R_t is the transmission range. The links capacities are set to 54 Mbps. The client arrival is modeled by a Poisson process with rate λ . Each client generates a flow with a uniform throughput demand between 1 and 10 Mbps, a delay bound of 4 hops and an exponential lifetime of mean $1/\mu = 90$ minutes. Other simulation parameters are summarized in Table II. Note that these test settings are partly taken from [15] and [18]. The results are obtained over many simulation instances for each scenario, with a margin error less than 5%, then we calculate the average value of performance metrics. For sake of presentation, we do not plot confidence intervals. Note that in what follows, we focus on energy consumption. Therefore, we set the parameters α_E to 0.9 and α_S, α_R to 0.05 each.

First, we study the impact of traffic load on our proposed approach. To do so, we vary the clients' arrival rate and measured the power consumption in the network for a simulation duration of 72 hours. Fig. 1(a) and Fig. 1(b) respectively show the total energy consumption for different arrival rates and the instantaneous power consumption in the network for $\lambda = 25$ requests/hour. From Fig. 1(a), we can notice that AC-OFFER reduces the power consumption compared to the other schemes, especially at medium arrival rates. Indeed, when $\lambda \in [10, 50]$, the power saving culminates at $3100 Wh^1$ representing a gain

¹ $Wh = 1 W$ consumption for a period of 1 hour. It represents the energy consumption.

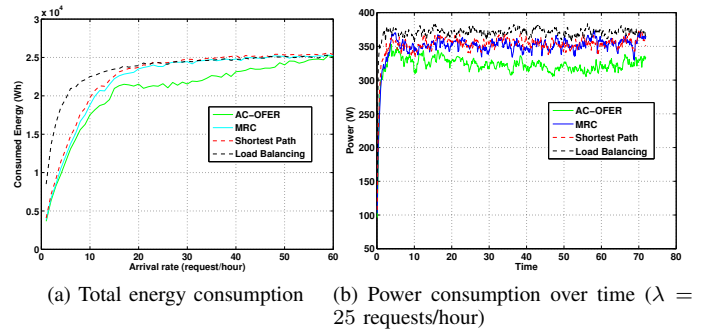


Fig. 1. Comparison of energy consumption (25 MAPs, 3 Gateways)

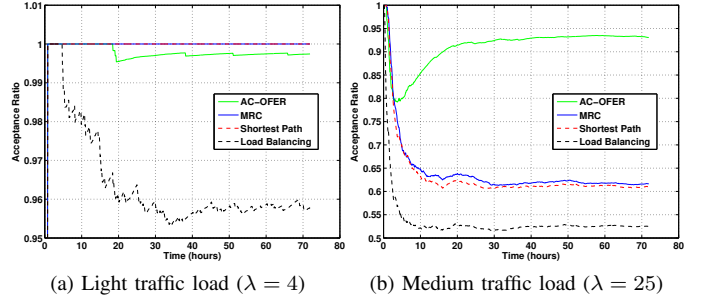


Fig. 2. Acceptance ratio for different traffic loads (25 MAPs, 3 gateways)

of 13%. On the other hand, for low arrival rates (i.e., $\lambda < 5$), the power saving is negligible because of the light traffic load in the WMN backbone. Note that LB is clearly not adapted for energy efficiency since the traffic is balanced over the whole network and thus uses maximum MAPs. In Fig. 1(b), we can appreciate how much our AC-OFFER approach contributes to reducing power consumption over time. In fact, the power saving is maintained around 12%, 16% and 22% for AC-OFFER compared to MRC, SP and LB, respectively.

To further show the benefit of our approach, we plot in Fig. 2 the acceptance ratio over time of all schemes for low and medium network loads (i.e., $\lambda = 4$ and 25 requests/hour). It is clear from the figure that for light traffic loads, all the approaches achieve high acceptance ratio. However, for the medium network load case (see Fig. 2(b)), AC-OFFER outperforms the other methods thanks to the dynamic reconfiguration achieved periodically (every 30 minutes in our simulations). This clearly helps to reduce resource fragmentation and have room for more flows to be accepted in the network.

Fig. 3 shows the performance evaluation of all schemes for the 100-node WMN case, in terms of acceptance ratio, average bandwidth per routed flow, energy consumption, used nodes, used gateways, and average path length. From this figure, we can observe that, AC-OFFER accepts as many flows as SP and MRC and more flows than LB. However, it reduces at the same time the energy consumption, the number of used nodes and the number of used gateways. Furthermore, the accepted flows are of the same demands, as illustrated in Fig. 3. Compared to SP, the gains are 20% for energy consumption, 19% for used MAPs, and 31% of used gateways. These gains are reduced to 13%, 11% and 27%, respectively, when compared to MRC, and increased to 52%, 53% and 39%, respectively, when compared to LB. These performances come, though, at the expense of a slightly higher average path length. In fact, AC-OFFER chooses paths with minimum energy consumption (i.e., paths that have

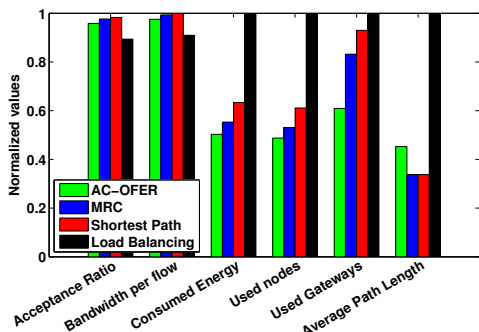


Fig. 3. Comparison of the average values of the different metrics (100 MAPs, 9 gateways, $\lambda = 5$ requests/hour)

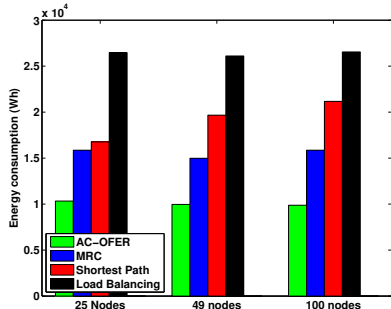


Fig. 4. Power consumption in 1-hop wireless networks ($\lambda = 20$ users/hour)

already been used by existing flows) to reduce the number of used nodes. Although the average path length increases, it remains acceptable since the delay constraints of flows (i.e., maximum number of hops) is always satisfied. Furthermore, the increase is not as much higher as in the LB approach, as illustrated in this figure.

Finally, Fig. 4 considers a special case of 1-hop wireless networks (i.e., each MAP is a gateway), which is more likely to be the case in corporate buildings, where APs are deployed with high density to handle peak demands. In this scenario, we consider different network sizes with users arrival rate $\lambda = 20$ users/hour. From this figure, we can see that AC-OFER reduces the energy consumption by up to 37%, 55%, and 61% compared to SP, MRC and LB, respectively, for the whole simulation duration (i.e., 72 hours). This is explained by the fact that with fixed in-building traffic ($\lambda = 20$ requests/hour), our scheme allows activating the same number of access points to serve directly the attached users. On the other hand, dynamic reconfiguration allows further energy saving compared to other approaches.

VII. CONCLUSION

In this paper, we investigated the energy management problem in WMNs. We proposed an online flow-based approach that takes into account the dynamic arrival and departure of clients by formulating the problem as an ILP and presenting an ant colony-based approach, called AC-OFER, to approximate the ILP optimal solution. Our objective is to minimize the energy consumption of the network, while routing dynamically the arriving and leaving flows subject to QoS constraints (i.e., bandwidth and delay). Through extensive simulations, we showed that AC-OFER achieves significant gains in terms of energy consumption, compared to Shortest Path (SP) routing, the Minimum link Residual Capacity (MRC) routing metric and the Load Balancing (LB) scheme, while ensuring the required QoS. More specifically, we showed that AC-OFER can enhance

the flow acceptance ratio, and at the same time reduce the energy consumption by up to 13%, 20%, and 52%, compared to MRC, SP, and LB, respectively. Moreover, we noted that, AC-OFER can easily be integrated in SDN-based WMNs. This approach represents therefore a promising solution for energy management in such networks..

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