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Energy efficient management framework for multihop TDMA-based wireless networks

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ABSTRACT

Green networking has recently been proposed to reduce energy cost as well as carbon footprint of computer networks. However, the application of green networking to multihop wireless networks has seldom been reported in the literature. This paper presents an energy-efficient framework for joint routing and link scheduling in multihop TDMA-based wireless networks. Our objective is to find an optimal tradeoff between the achieved network throughput and energy consumption. To do so, we first propose an Optimal approach, called Optimal Green Routing and Link Scheduling (O-GRLS), by formulating the problem as an integer linear program (ILP). As this problem is $\mathcal{NP}$-Hard, we then propose a simple yet efficient heuristic algorithm based on Ant Colony, called AC-GRLS. Through extensive simulations, we show that both approaches can achieve significant gains in terms of energy consumption, flow acceptance ratio and achieved throughput, compared to the Shortest Path (SP) routing, and the Minimum link Residual Capacity (MRC) based routing. In particular, we show that the same performance as SP or MRC in terms of average network throughput can be attained with up to 20% energy saving. On the other hand, with the same energy cost, our approaches enhance the flow acceptance ratio by up to 35% in average. This leads to a throughput increase of approximately 50% and 52% compared to SP and MRC routing, respectively.

1. Introduction

The Information and Communication Technology (ICT) consumes alone 3% of world wide energy consumption, and its CO_2 emission is around 2%, which is equivalent to airplanes emission and a quarter of cars emissions [1]. Combined with the fact that the cost of energy continues to rise, and the need for broadband expansion to rural areas, green networking has become one of the most important research directions in the ICT industry. To realize this goal, energy efficient communication has emerged as a promising solution to achieve sustainable and cost effective operations of communication networks.

The application of green networking to multihop wireless networks, in particular Wireless Mesh Networks (WMN), has seldom been reported in the literature. Typically, a WMN [2] comprises wireless mesh routers, also called access points (APs). Each AP serves multiple mobile users and connects them through multihop 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. 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].

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In this paper, we focus on TDMA-based wireless multihop networks since TDMA-based channel access facilitates the use of Quality of Service (QoS)-aware link scheduling and routing [4,5]. Indeed, while the IEEE 802.11 protocol is the de facto standard for multihop wireless networks, its MAC protocol (Carrier Sense Multiple Access with Collision Avoidance, CSMA/CA) performs poorly in WMNs and it is almost impossible to guarantee QoS [5,6]. To guarantee QoS, packet collisions must be avoided by scheduling interfering links to transmit in non-overlapping frequency or time intervals [5]. This is why several developments were provided using multihop MAC protocols based on TDMA, such as the IEEE 802.16 mesh protocol (e.g., WiMAX) [7], the 802.11s mesh deterministic access (MDA) protocol [8], and the software-based 802.11 overlay TDMA MAC protocol [5].

In this context, novel green and energy efficient routing and link scheduling strategies are needed to take into account energy consumption of wireless nodes when powered on. In this case, important questions arise: how many APs need to be active to route a traffic within a WMN and what is the optimal tradeoff between the achieved network throughput and energy consumption?

To answer these questions, we propose in this paper a holistic management framework that provides the WMN administrator with a parameterized objective function to achieve the desired tradeoff between 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. Here, we formulate the problem as an integer linear program (ILP). As this problem is known to be $\mathcal{NP}$-Hard [9,10], we then propose a simple yet efficient algorithm based on Ant Colony, called Ant Colony Green Routing and Link Scheduling (AC-GRLS) to solve it. The Shortest Path (SP) routing strategy and the Minimum link Residual Capacity (MRC) routing metric, are used to develop baselines to which AC-GRLS and O-GRLS are compared. Through extensive simulations, we show that our proposals can achieve significant gains in terms of energy consumption, flow acceptance ratio, and achieved throughput, compared to alternative solutions (i.e., SP and MRC). Specifically, we show that the same performance as SP or MRC in terms of average network throughput can be attained with minimum energy consumption. In this case, the energy saving is up to 20%. On the other hand, with the same energy cost, our approaches enhance the flow acceptance ratio by up to 35% in average. This leads to a throughput increase of approximately 50% compared to SP and MRC routing.

The reminder of this paper is organized as follows. Section 2 presents an overview of related works, followed by a description of the system model and the problem statement in Section 3. Section 4 describes our proposed framework for energy management through green joint routing and link scheduling. 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 5. Finally, Section 6 concludes this paper.

2. 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. The energy consumption metric in these works is either the number of shut down nodes or the shut down interfaces. A proposal in this direction is [11], where the authors propose to shut down nodes one by one and verify that the network still route the required traffic. Authors in [12] present results from a testbed of routers with multiple network interface cards. In [13], the authors address the online admission and flow-based routing problem in wired networks. Their approach uses the depth-first search method and a path length to find, for every flow, a feasible path (i.e., satisfying the required QoS) that requires the least number of nodes and links to be turned on.

Clearly, these schemes are not suitable for multihop wireless networks since the problem of interference between links limits the possibility to aggregate all traffic to reuse the same nodes.

On the other hand, an important body of work on energy-efficiency in cellular and WLAN systems has been reported in the literature. A survey on energy-efficient protocols for such networks can be found in [14].

In WLANs, authors in [15] present a centralized strategy that decides on which nodes (WLAN APs) to power on or off, according to users' demands. The obtained results show an important energy saving, which can attain 46%. In [16], authors proposed an analytical model to assess the effectiveness of the concept of Resource on Demand in WLANs and authors in [17] show management strategies for energy savings in solar powered 802.11 WMNs by turning off some APs. Similarly, authors in [18] proposed a theoretical framework based on queuing theory for energy saving in WLANs.

In cellular access networks, Masran et al. [19] propose to shut down some base stations during low traffic demands to reduce the overall energy consumption. Similarly, authors in [20] investigate energy saving procedures by turning off both transmission components during signal-free symbols and cells during low traffic periods. In [21], the authors propose a framework for green communications in wireless heterogeneous networks. This framework is cognitive in the holistic sense and aims at improving energy efficiency of the whole system.

In the context of WMNs, classical routing and link scheduling algorithms focus on the performance in terms of network throughput and delay. A survey of some of the existing works in literature is presented in [22]. However, these works did not address the energy consumption issue. Relevant works on energy-efficiency are reported in [23–28]. Specifically, authors in [23] present an energy saving approach in hybrid wireless-optical broadband access networks. They propose to reduce the energy consumption in the optical part of the network by shutting down an optical node whenever its load is below a threshold. At the same time, the traffic in the wireless part of the network is routed using the minimum residual capacity as a routing metric.

In [24], the authors consider the case of WMNs where the clients can choose the AP they connect to. To do so, they formulate 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. This work was extended in [25] to include the cost of nodes' deployment. In the latter, the objective is to choose between the energy cost and the deployment cost of a WMN. However, in these two works, the authors did 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 [26], where a combination between different modulation techniques and power adaptation is presented. Similarly, authors in [27] investigate control and optimization of energy consumption in mesh networks.

Authors in [28] present an energy and throughput-aware routing protocol in WMNs. The proposed algorithm admits as many flows as possible while satisfying their throughput guarantees, and at the same time uses as few nodes as possible by switching off the unused ones. The problem was formulated as a multi-commodity flow problem. However, the authors assume a pre-established channel assignment in the WMNs in order to avoid undesired interferences. In addition, the proposed routing protocol targets only 802.11-based WMNs.

In our study, we focus rather on energy efficient communications in TDMA-based WMNs by routing and scheduling the incoming traffic from clients to the mesh gateways (interconnecting the WMN to the wired network), while considering the interference between APs, the energy consumption as well as the achieved network throughput. Our goal is to find an optimal tradeoff between the two latter objectives. To achieve this, we first propose an optimal approach, by formulating the problem as an ILP, and then devise an Ant Colony based approximation to solve the formulated ILP problem with low time complexity. It is worth noting that the channel assignment is explicitly given by our proposed framework, as will be shown in Section 4.

3. System model

3.1. Network model

We represent a WMN by a directed graph $G(V,E)$, called a connectivity graph, where $V = \{v_1, \ldots, v_n\}$ is the set of n nodes and E is the set of possible direct communication 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, that provide the connectivity to the Internet. For simplicity, let $S = \{s_1, s_2, \ldots, s_m\}$ be the set of m gateway nodes, where s_i is the node v_{n+i-m}, for $1 \leqslant i \leqslant m$. All other wireless nodes v_i $(1 \leqslant i \leqslant n-m) \in V \setminus S$ are ordinary mesh nodes. Each ordinary mesh node will receive the traffic from all its attached users and then route it to the Internet through some gateway nodes. We assume that each node $v_i \in V$ has a limited capacity to serve its attached clients, denoted by C_i, whereas the capacity between any gateway node to the Internet (to forward its incoming traffic to the Internet) is sufficiently large.

During the transmission of the node $v_i \in V$, all the nodes residing in its transmission range, and thus representing its neighborhood denoted by $N_e(i)$, receive the signal from v_i with a power strength such that correct decoding is possible with high probability. A unidirectional wireless link exists between v_i and every neighbor $v_j \in N_e(i)$ and is represented by the directed edge $(i,j) \in E$. Each link (i,j) contains a certain number of orthogonal channels, denoted by nc_{ij}. The capacity along each channel k $(1 \leqslant k \leqslant nc_{ij})$ is limited and denoted by C_{ijk}.

We represent the connectivity graph $G(V,E)$ by a connectivity matrix, denoted by M. The connectivity matrix M is 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. Having the same structure, the number of channels in each link is modeled by a channel matrix, denoted by NC. If there is no direct link between i and j, then $nc_{ij} = 0$, and hence $C_{ijk} = 0$.

3.2. Interference model

In this paper, we adopt the protocol interference model [22]. In this model, a node v_j is interfered by the signal from v_i whenever $||v_i - v_j|| \leqslant R_I(i)$ and v_j is not the intended receiver. Recall that $||v_i - v_j||$ (denoted also by d_{ij} for simplicity) 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 on the same channel m (i.e., the receiver is interference free, as in [22]). Recall that the channels are assumed to be orthogonal. Hence, non-interfering links as well as interfering links operating on different channels can transmit in parallel during the same time slot. Note however that no simultaneous transmission and reception is allowed on the same node.

Given a connectivity graph $G(V,E)$, 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) on channel m interferes with the reception of the receiving node of link (p,q) on the same channel. The conflict graph F_G is then fully defined by the interference matrix I as follows:

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

3.3. AP energy consumption model

In this work, an AP can be in three different states: Active (i.e., Transmitting/Receiving), Idle and OFF. Note that in the Idle state, an AP is ON, but is neither transmitting not receiving. As reported through the experimental measurements in [29], the power consumption of an Active AP represents the peak power consumption, and an Idle AP consumes almost 75% of its peak power consumption. Finally, an OFF AP does not consume any power. As a result, we derive the following power consumption model for the power consumption P_i of an AP i as follows:

$$P_i = \begin{cases} 100\% & \text{If AP } i \text{ is Active} \\ 75\% & \text{If AP } i \text{ is Idle} \\ 0\% & \text{Otherwise} \end{cases}$$

3.4. Traffic model

In our study, we consider a set L of mesh users (also called clients). Each user $l \in L$ generates a certain traffic demand d_l (in terms of required bandwidth). To represent the user position within the WMN, we define a binary variable $a_{l,j}$ to indicate whether a user l is within the coverage area of the AP j or not. Note that a user l can be within the coverage area of multiple APs. Our aim is to turn off unnecessary APs to save energy, while achieving the required bandwidth of user l. The traffic demands of APs can follow a uniform distribution (i.e., each AP has the same demand) or a random process (e.g., Poisson process). According to [30], this traffic is assumed not to change during a given time interval. Indeed, in [30], 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 h are defined, as in [24]. In this paper, we adopt such characteristics. Without loss of generality, we assume that the traffic is uplink. This means that each originated traffic must be routed towards a gateway.

3.5. Problem formulation

The general problem we are considering aims at managing mesh nodes in order to save energy when some of the network resources (i.e., APs including gateways and the links connecting them) are not necessary and can be switched off, while achieving the required user's bandwidth. From an operational point of view, this can be easily integrated in network management platforms commonly used for carrier grade WMNs and to the centralized and remote control of all configured devices.

As we consider a slotted, synchronized WMN, and a static topology and demands (within one interval of 3 h, as stated in Section 3.4), it is reasonable to assume that the network is periodic with period T (i.e., each interval of 3 h is divided into a number of periods of length T, where the length is measured in time slots). For instance, using WiMAX, the scheduling period T corresponds to the frame duration which is 5–20 ms long [31].

As stated earlier, we jointly consider green routing and link scheduling. Recall that a link scheduling consists in allocating to each link a set of time slots $\subset \{1, \ldots, T\}$ on which it will transmit. 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 traffic towards the gateways to the number of needed time slots. Hence, maximizing the throughput boils down to minimizing the total number of used slots within the scheduling period T. The problem can be thus described mathematically within a WMN, as follows:

GIVEN:

- A physical topology represented by the graph $G(V, E)$, which is described by the connectivity, interference and channel matrices M, I and NC, respectively.
- A list L of clients, each one with its demand d_l.
- The coverage matrix A of APs, defined by the binary variable $a_{l,j}$.

FIND:

- The optimal attachment of each client among L to one of the covering APs and the optimal routing and link scheduling of its corresponding flow (traffic) that makes the best tradeoff between achieved network throughput and energy consumption.

In what follows, we present our proposed framework to achieve this goal.

4. Proposed framework for energy efficient management in TDMA-based WMNs

Our framework jointly considers green routing and link scheduling (GRLS) for energy efficient management in TDMA-based WMNs. It includes two methods: 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 $\mathcal{NP}$-Hard [9,10], we then propose a simple yet efficient algorithm based on Ant Colony meta-heuristic, called AC-GRLS, to solve it. A detailed description of these methods follows.

4.1. O-GRLS method

First, let us consider the binary variable $x_{ijk}^{(t)}(l)$ defined by:

$$x_{ijk}^{(t)}(l) = \begin{cases} 1 & \text{If traffic of client } l \text{ is routed from} \\ & i \text{ to } j \text{ using channel } k \text{ on time slot } t \\ 0 & \text{Otherwise} \end{cases}$$

and the binary variable w_{lj} that decides whether the client l will be attached to the AP j or not. To indicate whether an $AP_i \in V$ is ON or not, we introduce another binary variable y_i defined by:

$$y_i = \begin{cases} 0 & \text{If } \sum_{l \in L}\left(\sum_{t=1}^{T}\sum_{j=1}^{n}\sum_{k=1}^{nc_{ij}}(x_{ijk}^{(t)}(l) + x_{jik}^{(t)}(l)) + w_{li}\right) \\ & = 0 \\ 1 & \text{Otherwise} \end{cases}$$

To indicate whether an AP_i is active (i.e., transmitting or receiving) during a time slot t, we introduce the following binary variable $z_{i,t}$:

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

Consequently, the energy consumption of an AP_i during a period T is given by $\mathcal{P}_i$ as follows:

$$\mathcal{P}_i = \sum_{t=1}^{T} (z_{i,t} + (1 - z_{i,t}) \times y_i \times 0.75) \quad (1)$$

To indicate whether a time slot t is used for transmission, we also introduce the following binary variable z_t:

$$z_t = \begin{cases} 0 & \text{If } \sum_{i=1}^{n} z_{i,t} = 0 \\ 1 & \text{Otherwise} \end{cases}$$

Our ILP can be, thus, formulated as follows:

$$\text{Minimize } \left(\alpha \frac{\sum_{i=1}^{n} \mathcal{P}_i}{n \times |T|} + (1 - \alpha) \frac{\sum_{t=1}^{T} z_t}{|T|} \right) \quad (2)$$

where $|T|$ is the number of time slots in a period T. subject to:

$$\sum_{l \in L} x_{ijk}^{(t)}(l) \times d_l \leqslant C_{ijk} \quad \forall i,j \in \{1, \ldots, n\}, \\ k \in \{1, \ldots, nc_{ij}\}, \quad \forall t \in \{1, \ldots, T\} \quad (3)$$

$$x_{ijk}^{(t)}(l) + x_{pqk}^{(t)}(l') I_{(i,j),(p,q)} \leqslant 1 \quad \forall i,j,p,q \in \{1, \ldots, n\}, \\ k \in \{1, \ldots, nc_{ij}\}, \quad \forall t \in \{1, \ldots, T\}, \quad \forall l, l' \in L \quad (4)$$

$$\sum_{j=1}^{n} \sum_{l \in L} \sum_{k=1}^{nc_{ij}} x_{ijk}^{(t)}(l) + \sum_{j=1}^{n} \sum_{l \in L} \sum_{k=1}^{nc_{ji}} x_{jik}^{(t)}(l) \leqslant 1, \quad \forall t \in \{1, \ldots, T\}, \\ \forall i \in \{1, \ldots, n\} \quad (5)$$

$$x_{ijk}^{(t)}(l) = 0, \quad \forall i \in \{n - m + 1, \ldots, n\}, j \in \{1, \ldots, n\}, \\ k \in \{1, \ldots, nc_{ij}\}, \quad \forall l \in L, \quad \forall t \in \{1, \ldots, T\} \quad (6)$$

$$\sum_{t=1}^{T} \sum_{j=1}^{n} \sum_{k=1}^{nc_{ij}} x_{ijk}^{(t)}(l) \leqslant 1, \sum_{t=1}^{T} \sum_{j=1}^{n} \sum_{k=1}^{nc_{ji}} x_{jik}^{(t)}(l) \leqslant 1, \\ \forall i \in \{1, \ldots, n\}, \quad \forall l \in L \quad (7)$$

$$\sum_{l \in L} \sum_{t=1}^{T} \sum_{j=1}^{n} \sum_{k=1}^{nc_{ij}} x_{ijk}^{(t)}(l) = \sum_{l \in L} \sum_{t=1}^{T} \sum_{j=1}^{n} \sum_{k=1}^{nc_{ij}} x_{jik}^{(t)}(l) \\ + \sum_{l \in L} w_{li} \left(\sum_{t=1}^{T} \sum_{j=1}^{n} \sum_{k=1}^{nc_{ij}} x_{ijk}^{(t)}(l) \right), \quad \forall i \in \{1, \ldots, n - m\} \quad (8)$$

$$\sum_{t=1}^{T} \sum_{i=1}^{n} \sum_{j=n-m+1}^{n} \sum_{k=1}^{nc_{ij}} x_{ijk}^{(t)}(l) + \sum_{j=n-m+1}^{n} w_{lj} = 1 \quad \forall l \in L \quad (9)$$

$$w_{ij} \leqslant A_{ij} \quad \forall i,j \in \{1, \ldots, n\} \quad (10)$$

$$\sum_{l \in L} w_{lj} \times d_l \leqslant C_j \quad \forall j \in \{1, \ldots, n\} \quad (11)$$

$$\sum_{j=1}^{n} w_{lj} = 1 \quad \forall l \in L \quad (12)$$

$$x_{ijk}^{(t)}(l), y_i, z_t, z_{i,t}, w_{lj} \in \{0, 1\} \quad \forall i,j \in \{1, \ldots, n\}, \\ \forall l \in L, \quad \forall t \in \{1, \ldots, T\} \quad (13)$$

where $\alpha \in [0, 1]$ is a weighting coefficient determining the tradeoff between the achieved throughput and the 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. Note that these two terms are normalized by dividing the first one by the number of APs and the total number of available time slots; and the second term by the total number of available time slots.

Condition (3) ensures not transmitting over a non-existing link as well as not exceeding the capacity of a link. Condition (4) implies that interfering links are not scheduled to transmit in the same time slot. The constraint in (5) prevents a node from simultaneous sending and receiving, or receiving from multiple senders, or sending to multiple receivers during the same time slot, as in [32]. However, this constraint could be relaxed as in [33] to enable receiving and sending at the same time on the same channel (Full Duplex), or sending and receiving on different orthogonal channels at the same time slot (Frequency Division). Condition (6) 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 towards the Internet. Condition (7) avoids loops while routing a flow originating from client l. Condition (8) refers to the flow continuity constraint, which ensures the routing path to be continuous. It ensures that all the incoming flows are routed in addition to the flows originating from the clients that are attached to the node. That is, the number of flows that come into an AP (from both its neighboring APs and its attached clients) is equal to what goes out of this AP (towards its corresponding neighboring APs), except the gateways that route the traffic towards the Internet. Condition (9) ensures that all the flows are successfully routed to one of the available gateways within the time period T. Conditions (10) and (11) guarantee no attachment to non-covering AP and not exceeding the capacity of an AP, respectively. Condition (12) guarantees that each client is connected to at most one AP. The last condition indicates that $x_{ijk}^{(t)}(l)$, y_i, w_{lj} $z_{i,t}$ and z_t are binary variables.

It is worth noting that in this ILP, we do not consider data fragmentation at multiple points in the network, as splitting traffic flows can increase jitter due to out of sequence arrival of packets [34]. However, we note that if a user's demand d_l is higher than the channel capacity, its corresponding traffic will be split into different parts of size p that satisfy the link capacities. Then, each part will be considered as a separate flow corresponding to a different "virtual" user.

4.2. AC-GRLS method

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: $q_0,\ \alpha_{ANT},\ \beta_{ANT},\ Q$
Initialize pheromone trails
best_solution ← some initial solution
for $nb = 1 \rightarrow$ Number of Iterations **do**
  Construct Ant Solutions
  for all ant in A_{max} **do**
    current_solution ← {}
    for $l = 1 \rightarrow$ Number of clients **do**
      $p \leftarrow Random(0, \ldots, 1)$
      if $p < q_0$ **then**
        Choose path j where
        $j = Argmax_{k \in N_l}\left(\tau_{lk}^{\alpha_{ANT}} \times \eta_{lk}^{\beta_{ANT}}\right)$
      else
        Choose path j according to P_{lj} probability
        $P_{lj} = \frac{\tau_{lj}^{\alpha_{ANT}} \eta_{lj}^{\beta_{ANT}}}{\sum_{k \in N_l} \tau_{lk}^{\alpha_{ANT}} \eta_{lk}^{\beta_{ANT}}}$
      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 ← current_solution
    end if
  end for
  Pheromone trail update
  for $l = 1 \rightarrow$ Number of flows **do**
    for $j = 1 \rightarrow K$
      $\tau_{lj} \leftarrow (1-\rho)\tau_{lj}$
      if current_solution is the best solution for the current iteration And jth path is selected for client l **then**
        $\tau_{lj} \leftarrow \tau_{lj} + \Delta_{lj}^{best}$
      end if
    end for
  end for
end for
Return best_solution

The ILP formulation presented in the previous subsection 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. Specifically, 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, we propose here a simple yet efficient meta-heuristic based algorithm, called AC-GRLS.

AC-GRLS is based on the Ant Colony System meta-heuristic [35], which takes inspiration from the behavior of collective ants in finding the best path between their nest and a food source. It operates as follows. First, a set of solution components (i.e., paths) needs to be determined for each flow coming from a client. Next, A_{max} artificial ants are launched and iteratively explore the search space until a predetermined number of iteration N_{max} is reached. During each iteration, each ant among A_{max} incrementally constructs the solution by adding in every step one solution component (i.e., a path for one client's flow) to the partial solution constructed so far. Note that the solution component to add among the candidates is chosen using a stochastic local decision policy. More specifically, the decision is based on *heuristic* information, denoted by η, and artificial *pheromone trails*, denoted by τ, which respectively quantify the desirability of a priori and a posteriori transition. Indeed, the *heuristic* represents the attractiveness of the move, indicating the a priori desirability of that move. On the other hand, the *pheromone trails* indicate how proficient it has been in the past (i.e., according to other ants experience) to add that solution component. Once an ant has built a solution, or while the solution is being built, the ant evaluates the partial solution and deposits pheromone trails on the components it used. This pheromone information will direct the search of the future ants.

Once each ant has build its full solution, the best one (i.e., the one that most enhances the objective function, given in Eq. (2)) among all solutions generated by all ants is selected. Furthermore, the artificial pheromone slightly evaporates in all the environment. This helps the ants to discover new trajectories and to avoid a too rapid convergence to local optima. Nevertheless, the artificial pheromone trail of each solution component is reinforced at the visited points according to the best trajectory traveled by ants to build the whole solution. This helps the ants to improve and continually refine the best obtained solution. The process is repeated during N_{max} iterations and the global best solution generated by the A_{max} ants is considered to be the output solution. More formally, our AC-GRLS algorithm is described by the pseudo-code in Algorithm 1.

Algorithm 2. Greedy Link Scheduling

IN: LS: List of links to schedule, the conflict graph.
OUT: Sc: List of Slots with the corresponding scheduled links in each slot.
$Sc \leftarrow \{\};\ i \leftarrow 0$ //i is the current slot
while $LS \neq \emptyset$ **do**
  //Extend Sc by one slot
  $i \leftarrow i + 1;\ Sc[i] \leftarrow \{\}$
  for all $ls \in LS$ **do**
    for all $k \in channels(ls)$ **do**
      if ls_k does not interfere with any link in $Sc[i]$ **then**
        $Sc[i] \leftarrow Sc[i] \cup \{ls_k\}$;
        Remove ls from LS
        Break;
        //Move to the next link to schedule
      end if
    end for
  end for
end while
Return Sc
The returned list Sc contains the slots and, for each slot, the links that are scheduled to transmit as well as the corresponding channels.

The fundamental steps of AC-GRLS are: (1) Formation of solution components, (2) Probabilistic selection of the candidate, (3) Selection of the best solution and (4) Updating the pheromone trails. In the following, we detail these stages.

(1) *Formation of solution components:* For each client, we consider K alternative paths towards a gateway (any of the m available gateways). Each path starts from the client, passes through an AP that the client attaches to, and then other intermediate APs until reaching a gateway. A solution component will be one of the predetermined K paths. As such, the number of possible solutions for the path formulation is $K^{|L|}$, where $|L|$ is the number of clients. Hence the proposed meta-heuristic guides the algorithm to efficiently explore the graph of solutions.

(2) *Selection among the candidates for a component:* During each iteration, each ant among A_{max} builds the solution step by step, by adding in each step another component (i.e., a path for a flow from client 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:

$$\eta = \frac{1}{\text{Objective Function Value}} \tag{14}$$

Note that, to compute the objective function value given in (2), a greedy link scheduling algorithm (presented in Algorithm 2) is used to schedule transmissions along all paths that form the new constructed solution. Once computed, the choice of the next component to add to the partial solution constructed so far (i.e., a path j for a client l) is selected according to a given probability. Note that in Ant Colony System meta-heuristic [35], two strategies can be used: *exploitation* and *exploration*. More specifically, *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 stochastically taken into account. Indeed, the next component is selected according to a probability P_{lj} given by:

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

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 Eq. (14), and the pheromone trail of the jth path for the flow originating from client l, and α_{ANT} and β_{ANT} determine, respectively, the relative importance of τ_{lj} and η_{lj}. Recall that η_{lj} represents the desirability of adding the solution component j (i.e., path j) to route the flow of client l, whereas τ_{lj} represents how proficient it has been so far to route the flow of client l through path j. As such, α_{ANT} and β_{ANT} parameters have the following influence on the algorithm behavior. If $\beta_{ANT} = 0$, the selection probabilities are portional to the heuristic value η_{lj}, which means that the components with high heuristic value are more likely to be selected. In this case, AC-GRLS corresponds to a classical stochastic greedy algorithm. However, if $\alpha_{ANT} = 0$, only pheromone amplification is at work: the components with high pheromone trail are more likely to be selected, in which case a rapid convergence to a suboptimal solution may result as all ants are more likely to build the same solution.

On the other hand, in *exploitation*, the experience of the other ants is directly 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.

(3) *Selection of the best solution:* The criterion to choose the best solution is the objective function given in Eq. (2), which makes the tradeoff between network throughput and energy consumption.

(4) *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 $\rho \in [0, 1]$ 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 $\eta^{best} = 1/\textit{Objective function value of the best solution}$, as reported in Eq. (14).

5. Performance evaluation

In this section, we evaluate the efficiency of our proposed framework. Specifically, we study the gain that both O-GRLS and AC-GRLS introduce compared to the Shortest Path (SP) routing and the Minimum link Residual Capacity (MRC) routing metric [23], 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. We consider different grid-based WMN topologies: 25 (5×5) APs with 4 gateways (located at the 4 corners of the grid), and 100 (10×10) APs with 9 gateways, which are representative of small and large-sized WMNs, respectively. The nodes are located in an area of 1000 m × m. Based on the transmission range $R_t = 250$ m of each AP, and the interference range $R_I = 1.5 \times R_t$, both the connectivity and conflict graphs are derived. Then, according to users positions, which are uniformly distributed within the network, the coverage matrix A is derived. In our simulations, we consider different numbers of connected users (2–40 for the 25-node WMN case, and 5–170 for the 100-node WMN case) to show the impact of network load on the evaluated metrics. Without loss of generality, we normalize the channel bandwidth capacities to a value of 1. The clients' demands are expressed in percentage of the channel capacities. Note that if a client's demand is higher than the channel capacity, its corresponding traffic will be split into different parts of size p that satisfy the link capacities. Then, each part will be considered as a separate flow corresponding to a different "virtual" user. In addition, we vary the weighting factor α to determine the best tradeoff between energy consumption and throughput. As in [36], the scheduling period T is set to 5 ms, which corresponds to 48 time slots.

The performance metrics used in our simulations concern the computation time, the objective function value given in Eq. (2), the energy consumption which represents the normalized value of consumed energy given by:

$$\mathcal{P} = \frac{\sum_{i=1}^{n} \mathcal{P}_i}{n \times |T|} \quad (15)$$

where $\mathcal{P}_i$ is the power consumption of an AP i as given in Eq. (1), n is the number of APs and $|T|$ is the number of available time slots within the period T. Moreover, additional metrics such as the proportion of used nodes (i.e., relay APs as well as used gateways), which contributes the most to the energy consumption used to forward the required traffic of L clients, the flow acceptance ratio and the achieved throughput. Additional metrics such as the average path length are also investigated.

The reported results are obtained using the solver *ILOG CPLEX* [37] for O-GRLS and a *Java* implementation for AC-GRLS, SP and MRC. Table 1 reports the simulation parameters used for AC-GRLS. Note that there is no optimal rule for setting the values of parameters β_{ANT}, α_{ANT}, ρ, q_0, the number of ants and the number of iterations, as pointed out in [38,39]. Hence, we experimentally tuned these parameters by running preliminary tests using different values of each of them. We then chose the most interesting values that offer satisfactory results. Note that our simulations are run until a narrow 95% confidence interval is achieved. Note also that to achieve such narrow confidence intervals, simulations need to be run in certain cases over several hours up to more than one day, notably when the number of APs is large.

The analysis is divided into two parts. First, we present results related to the particular case of single channel WMNs. Then, we investigate the case of multichannel TDMA-based WMNs, which is more likely to be the case in real networks.

5.1. Single channel WMNs

To get an insight into the convergence of our Ant-Colony approach (i.e., AC-GRLS) to the optimal solution (i.e., O-GRLS), let us first consider here both Table 2 and Fig. 1. Specifically, Table 2 reports the computation time needed by all methods to resolve the GRLS problem. These measurements are performed on a PC with 3.2 GHz of CPU and 4.00 GB of RAM. The reported results show that the Ant-Colony approach takes a very short time to solve the problem (up to 5 s in the small-sized WMN case, and up to 12 s in the large-sized one), compared to the optimal one, which can reach 600 s. The SP and MRC algorithms, however, need less than 1 s (in the 25 APs case) since no energy saving is considered.

On the other hand, Fig. 1 compares the objective function values of the afore-mentioned strategies, while varying α and under different network loads for small-sized WMNs. We can observe that the mean values obtained for O-GRLS fit or are very close to the confidence intervals of AC-GRLS. This means that the Ant-Colony approach yields a very good approximation to the optimal solution and within a short time period as reported in Table 2. We can also observe that we succeed to reduce the objective function value by up to 50% using AC-GRLS compared to the SP and MRC routing strategies. Let us now focus on the comparison between the different methods based on the energy cost and the achieved network throughput.

Fig. 2 shows the achieved throughput, the energy consumption, the proportion of used nodes, as well as the average path length in small-sized WMNs. We can observe that the energy cost and the achieved throughput decrease with the increase of α for both O-GRLS and AC-GRLS, and remain invariant for SP and MRC since these two latter schemes do not take into account the energy consumption and the achieved throughput in the flow routing process, respectively. In particular, when $\alpha = 1$, the consumed energy is set to minimum but at the expense of low achieved throughput.

The main observation for AC-GRLS here is when $\alpha \in [0.4, 0.7]$ compared to SP and $\alpha \in [0.5, 0.78]$ compared to MRC. Indeed, within these ranges of α, our proposed framework achieves better throughput than both SP and MRC strategies [see Fig. 2(a)], and at the same time consumes less energy and uses a reduced number of relaying nodes [see Fig. 2(b) and (c)]. 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 consuming less energy. In this case, the energy saving is about 14% and 19% for AC-GRLS and O-GRLS, respectively. Whereas, for $\alpha = 0.4$, the network consumes the same energy as SP when using AC-GRLS, but at the same time achieves a higher network throughput. The gain culminates at 50% in this case. The same reasoning holds when compared to MRC. In fact, on one hand, for $\alpha = 0.78$, an operator succeeds in achieving the same performance as MRC by consuming 14% less energy. On the other hand, for $\alpha = 0.5$, for the same energy budget, AC-GRLS achieves higher throughput than MRC by about 52%. It is worth noting that, since AC-GRLS, MRC and SP use a simple greedy link scheduling (reported in Algorithm 2), the achieved network throughput shown here can be viewed as a lower bound of the possible achieved one when using other "advanced" link scheduling algorithms.

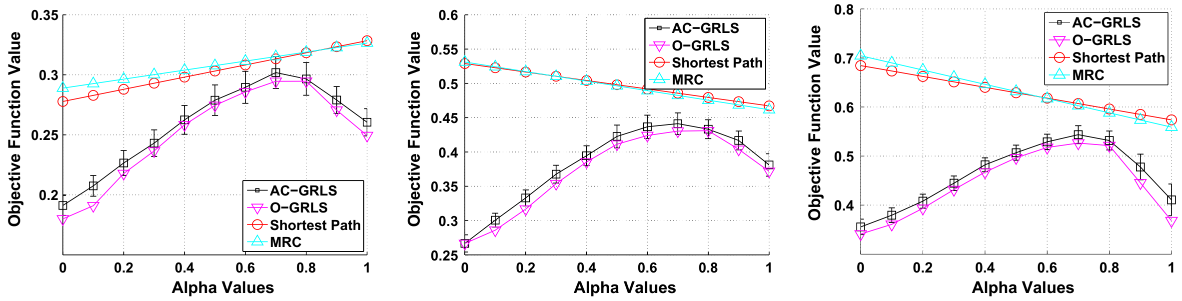
Another important usage of the above results is the selection of the best value of α to guarantee a certain network throughput, while reducing the total energy cost. This could be used by the WMN administrator to seek a

Table 1
AC-GRLS simulation parameters.

Parameter	Value	Parameter	Value
α_{ANT}	0.15	ρ	0.2
β_{ANT}	1.2	# of Ants	6
Q	$\lvert L\rvert$	# of iterations	10
q_0	0.1	T	48 slots

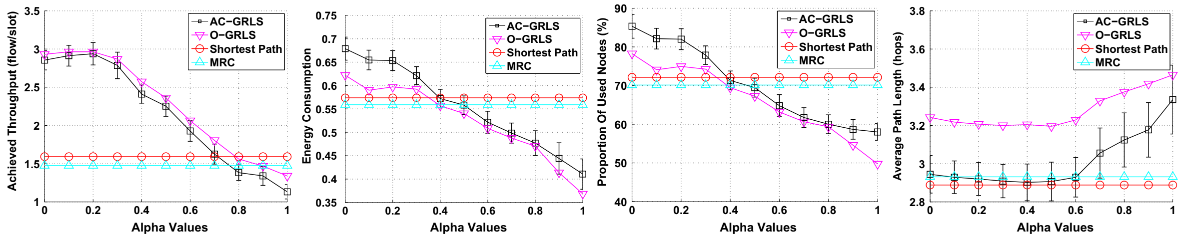
Table 2
Computation time (in seconds) for O-GRLS, AC-GRLS, MRC, and SP schemes.

Network size	# of clients	O-GRLS	AC-GRLS	MRC	SP
25 nodes	5	265.32 ± 24.75	0.42 ± 0.38	0.03 ± 0.02	0.05 ± 0.03
4 gateways	10	532.81 ± 16.59	1.83 ± 2.21	0.45 ± 0.14	0.41 ± 0.15
	15	597.14 ± 13.29	3.42 ± 5.22	0.91 ± 0.25	0.86 ± 0.17
100 nodes	25	–	7.22 ± 2.75	0.41 ± 0.15	0.43 ± 0.15
9 gateways	50	–	9.14 ± 3.2 3	1.33 ± 1.23	1.66 ± 1.14
	75	–	11.21 ± 4.39	3.63 ± 0.33	3.51 ± 0.29



(a) 5 clients (b) 10 clients (c) 15 clients

Fig. 1. Comparison of the objective function values for O-GRLS, AC-GRLS, SP and MRC in small-sized WMNs.



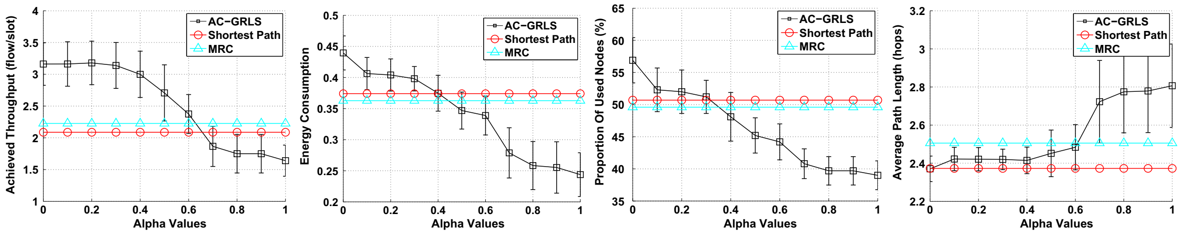
(a) Achieved throughput (flow/slot) (b) Energy consumption (c) Proportion of used nodes (%) (d) Average path length

Fig. 2. Simulation results for O-GRLS, AC-GRLS, SP and MRC in small-sized WMNs with 15 clients.

desired tradeoff. For instance, if one wants to achieve, at least, a throughput of 2*flow/slot*, a value of $\alpha = 0.58$ could be selected when adopting AC-GRLS.

To show the scalability of our AC-GRLS approach, we carried out additional simulations in large-sized WMNs with different number of connected mesh clients. Results for the case of 95 mesh clients are presented in Fig. 3. Same observations can be made here. Indeed, we can see that for $\alpha = 0.65$ and $\alpha = 0.62$, almost the same throughput as SP and MRC, respectively, is achieved, while consuming less energy. The energy saving is about 20% and 11% compared to SP and MRC, respectively. However, with the same energy cost, better throughput is achievable with AC-GRLS, as shown in Fig. 3(a). In fact, the throughput gain can attain 47% and 28% compared to SP (for $\alpha = 0.4$) and MRC (for $\alpha = 0.42$), respectively. Note that, results regarding O-GRLS are not provided here due to the inherently high computation time.

Regarding the average path length, depicted in Fig. 3(d), we can observe that the SP algorithm obviously selects paths with minimum number of hops towards the gateways. Both MRC and AC-GRLS, on the other hand, choose longer paths than SP to reduce the number of used nodes. However, we notice that the paths selected by AC-GRLS have the tendency to be the same as in MRC, in particular when $\alpha \leqslant 0.7$. Indeed, as shown in Fig. 3(d), when $\alpha = 0.42$ (i.e., same energy cost as MRC), the average path length is better than MRC. This means that our approach can achieve high network throughput without increasing not only the energy cost but also the average path length. This will help to achieve efficient end-to-end delay, as longer paths might result in high delays due to packet forwarding. Indeed, the delay in WMNs is a function of the number of communication hops between the source and the gateway), as shown in [40]. Specifically, WMN scales better when the traffic pattern is Local. That is, each node sends only to nearby gateways (and not to far away gateways), independent of the network size. The expected path length clearly remains a few hops away from the gateway as the network size grows. On the other hand, when $\alpha = 0.65$ (i.e., in the case of achieving lower energy cost than both SP and MRC



(a) Achieved throughput (flow/slot) (b) Energy consumption (c) Proportion of used nodes (%) (d) Average path length

Fig. 3. Simulation results for AC-GRLS, SP and MRC in large-sized WMNs with 95 clients.

with approximately the same achieved throughput), the average path length is slightly higher than with MRC. This shows that even though our approach uses slightly longer paths than the MRC strategy, the energy cost is not affected since the flows are routed through already active nodes, thus enabling energy saving.

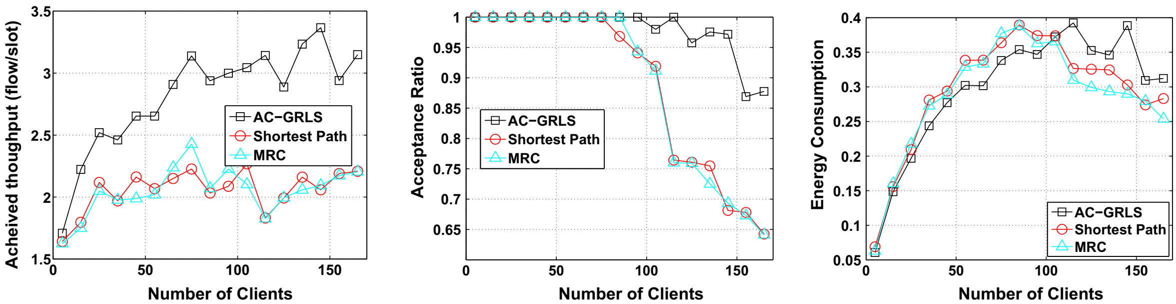
It is worth noting that comparable results have been obtained in the case of arbitrary meshed topologies of the same sizes. Indeed, compared to SP, MRC achieves energy saving of around 7%. AC-GRLS, on the other hand, reduces the energy cost by about 16% for both small and large-sized WMNs. However, the achievable network throughput improvement is about 29% and 30% compared to SP and MRC, respectively, in small-sized WMNs. These gains are reduced to 26% and 24%, respectively, in the large-sized WMN case.

Figs. 4 and 5 further investigate the scalability of our Ant-Colony approach when varying the network load for the particular cases of $\alpha = 0.45$ (i.e., same energy cost as MRC) and $\alpha = 0.75$ (i.e., same achieved throughput as MRC), respectively. Note that to vary the network load, we vary the number of attached mesh clients. From both figures, we can observe that:

- AC-GRLS persistently outperforms the other methods, with relevant differences at high network load. Indeed, it shows a throughput increase of approximately 60% compared to SP and MRC, while using the same energy budget [see Fig. 4(a) and (c)].
- The throughput of all approaches globally increases with the number of users in the network (i.e., network load) till reaching the full WMN capacity (in terms of attached users)under AC-GRLS, SP, or MRC and using our greedy link scheduling algorithm. For instance, this capacity corresponds to 125 users for AC-GRLS, 75 and 85 users for SP and MRC, respectively, when $\alpha = 0.45$, as shown in Fig. 4(b). Beyond these points, the network starts rejecting incoming flows since the total number of available slots in the network is fixed (48 time slots in our simulations).
- AC-GRLS enhances the flow acceptance ratio by up to 35% compared to both SP and MRC [see Figs. 4(b) and 5(b)].
- The energy cost kept increasing with the network load since more and more nodes will be turned onto forward the traffic [see Figs. 4(c) and 5(c)]. However, the energy cost tends to flatten when the number of clients increases as flows are rejected and no additional energy is consumed (see Fig. 5(c), number of clients above 120).
- AC-GRLS achieves similar network throughput in average compared to SP and MRC for $\alpha = 0.75$, while minimizing the energy cost, especially at medium and high network load (see Fig. 5). In this case, the energy saving culminates at 29%.
- At low network load, the gain of AC-GRLS over the other schemes is not significant due to traffic scarcity.

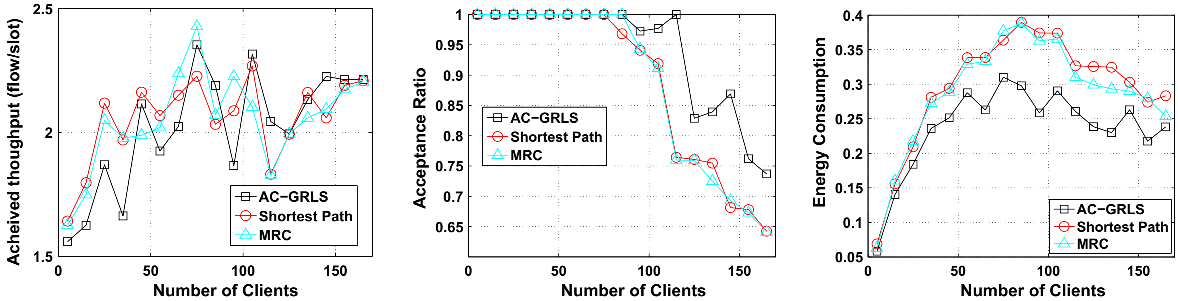
5.2. Multichannel WMNs

In this subsection, we analyze the impact of using multichannel WMNs on the performance of our proposed AC-GRLS approach.More precisely, these results aim to show that our approach is still effective in multichannel networks, in contrary to other approaches such as MRC. In



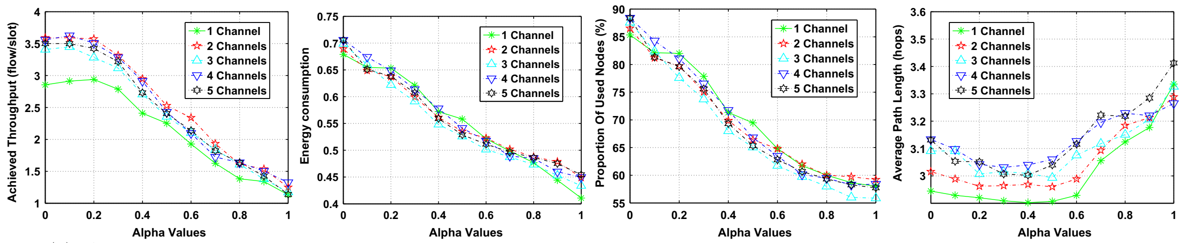
(a) Achieved throughput (flow/slot) (b) Flow acceptance ratio (c) Energy consumption

Fig. 4. Achieved throughput, flow acceptance ratio, and proportion of used nodes vs. number of mesh clients (100 nodes, 9 gateways, $\alpha = 0.45$).



(a) Achieved throughput (flow/slot) (b) Flow acceptance ratio (c) Energy consumption

Fig. 5. Achieved throughput, flow acceptance ratio, and proportion of used nodes vs. number of mesh clients (100 nodes, 9 gateways, $\alpha = 0.75$).



(a) Achieved throughput (flow/slot) (b) Energy consumption (c) Proportion of used nodes (%) (d) Average path length

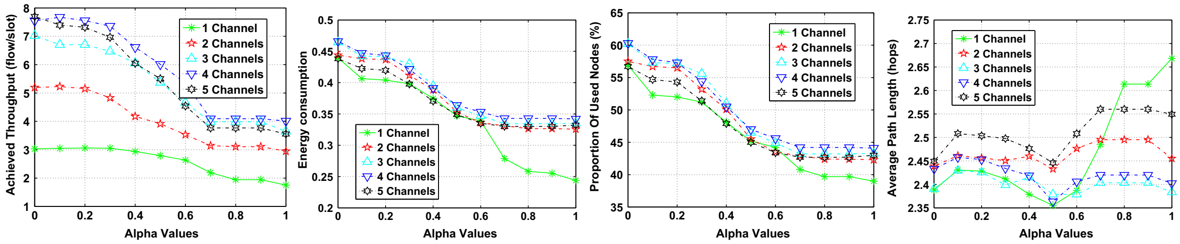
Fig. 6. Impact of number of sub-channels on AC-GRLS in small-sized WMNs with 15 clients.

fact, one issue when minimizing energy is the bottlenecks that might result at the gateways level. As the interference limits the capacity of the WMN, adding channels may lead to small improvement in performance, as will be shown hereafter. To do so, we vary the number of sub-channels[1] from 1 to 5 using the afore-mentioned simulation topologies and traffic loads. The results are depicted in Figs. 6 and 7, for small- and large-sized WMNs, respectively. We can here appreciate how much the use of multiple channels contributes in increasing the achieved network throughput, without impacting the energy cost. In particular, we can observe that:

- For small-sized WMNs, the throughput gain is maintained at 24%, compared to the single channel WMN case [see Fig. 6(a)]. On the other hand, this gain is increased by up to 150% and 100% at low/medium and high values of α, respectively, in large-sized WMNs [see Fig. 7(a)].
- The maximum throughput gain is achieved by using 3 and 4 sub-channels for small- and large-sized WMNs, respectively. Non-relevant differences are observed beyond these values. This is explained by the fact that the network performance is near optimal in this case.
- The energy consumption and the proportions of used nodes remain globally the same even though some differences can be observed in Figs. 6(c) and 7(c). This is mainly due to the randomness in our simulations since we use a different topology for each test.
- From the path length point of view, no significant changes are observed since the average path length is almost equal to 3 hops for the small-sized WMNs case and between 2.3 and 2.7 hops for the large-sized one, as shown in Figs. 6(d) and 7(d).

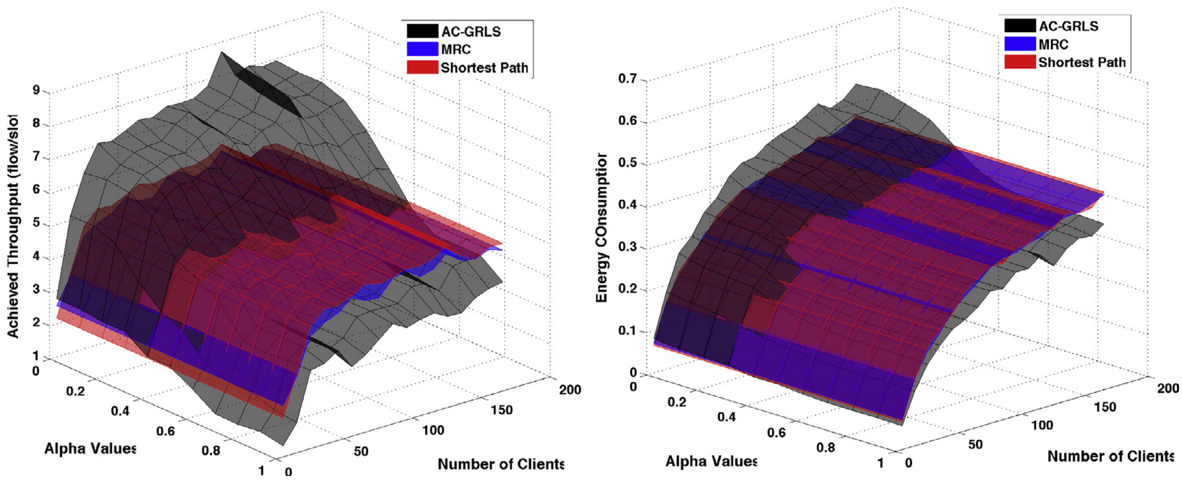
Finally, Fig. 8(a) and (b) illustrate, respectively, the achieved throughput and the energy consumption when varying the network load as well as the coefficient factor α, for the 100 node WMN case and using 4 sub-channels. Recall that, with 4 sub-channels, we can reach the maximum WMN performance under AC-GRLS, as shown in Fig. 7. Same observation can be made here. Indeed, when $\alpha = 0.55$, on average, while the three approaches achieve the same network throughput, AC-GRLS reduces the energy cost by up to 19% for the different numbers of users. On the other hand, when $\alpha = 0.4$, the Ant-Colony approach enhances the achieved throughput by up to 30% and 38% compared to SP and MRC, respectively, while incurring the same energy cost. Note that no significant improvement is observed at low network load due to traffic scarcity. On the other hand, at high network load, the improvement in achieved throughput is bounded by the channel capacity as well as the interference between wireless links. It is worth noting that, in multichannel WMNs, while AC-GRLS maintains the gains in terms of achieved throughput and energy consumption compared to SP, MRC performs poorly in the multichannel case since it achieves similar performance as SP. Note that in single

[1] The terms *channel* and *sub-channel* are used interchangeably. Both refer to a sub-channel.



(a) Achieved throughput (flow/slot) (b) Energy consumption (c) Proportion of used nodes (%) (d) Average path length

Fig. 7. Impact of number of sub-channels on AC-GRLS in large-sized WMNs with 95 clients.



(a) Achieved Throughput (b) Energy consumption

Fig. 8. Achieved throughput and consumed energy when varying the number of mesh clients and α (100 nodes, 9 gateways, 4 sub-channels).

channel WMNs, MRC performs better than SP. The explanation for this stems from the fact that when adding channels, the gateways are still a bottleneck. In fact, a gateway cannot receive from multiple neighbors as depicted by Eq. (5), which limits the utilization of the multiple channels. As MRC does not take into account this issue in multichannel WMNs, the throughput degrades which results in performance comparable to SP.

6. Conclusion

In this paper, we investigated energy management efficiency in multihop TDMA-based Wireless Mesh Networks (WMNs). Specifically, we have proposed a holistic 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 find a good tradeoff between the achieved network throughput and energy consumption using a parameterized objective function. The latter provides network administrators with a means 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 throughput and flow acceptance ratio, compared to the Shortest Path (SP) routing and Minimum Residual Capacity (MRC) routing metric. In particular, we showed that in small-sized WMNs, our proposed framework saves 13% (14%, respectively) of the energy cost, while achieving the same performance as SP (MRC, respectively). However, if the network consumes the same energy as SP (MRC, respectively), the achieved throughput can be enhanced by up to 50% (52%, respectively). On the other hand, in large-sized WMNs, the energy saving is about 20%, while the achievable throughput improvement is about 47%. In addition, we showed that our framework enhances the flow acceptance ratio by up to 35% and achieves better performance even at high network load. However, this improvement is bounded by the channel capacity as well as the interference between wireless links. Furthermore, we showed that using multiple sub-channels aims at increasing the achieved network throughput without impacting on the energy consumption. Finally, we demonstrated 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 effective solution for energy efficient management in TDMA-based WMNs.

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