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# Energy Efficient Management for Wireless Mesh Networks with Green Routers

Sarra Mamechaoui<sup>1</sup> · Sidi Mohammed Senouci<sup>2</sup> · Fedoua Didi<sup>1</sup> · Guy Pujolle<sup>3</sup>

**Abstract** Wireless Mesh Networks (WMNs) consist of a high-density of hundreds to thousands of mesh routers (MRs) deployed in corporate offices and university campuses. The main purpose of this deployment is to meet user demands for high bandwidth, mobility, and reliability. However, our recent consideration of such networks revealed that they are rarely used at their peak capacity besides the fact that the entire MRS remains active continuously. Thus, during lower traffic periods the energy consumption is the same as in busy hours, while it would be possible to save a large amount of power. Green networking has recently been proposed; consist of rethink how networks are constructed and operated so that not only the cost and performance are taken into consideration but also their energy consumption and carbon footprint. In this paper, we draw attention that a large part of idle MRs results in considerable energy losses. Thousands of WMNs worldwide jointly aggravate this problem, while raising serious worry about the energy wastage that will happen in the future. In response to this problem, we first propose an optimal approach called Optimal Energy Efficiency Management Design (OEEMD) by formulating the problem as a Mixed

Integer Linear Program (MILP) model to investigate the power consumption in WMN. As this problem is known to be NP-hard, we then propose an efficient heuristic algorithm called Green Energy Efficiency Management Design (GEEMD) for wireless mesh networks. GEEMD uses a sleep mechanism to power on/off underutilized MRs, based on the traffic load and solar energy generation. For the performance evaluation, we used OEEMD and GEEMD to study the performance of WMN deployment scenario in the university and campus area of Tlemcen city in Algeria over dynamic traffic profiles. Illustrative numerical examples show that, with suitable design parameters, we can efficiently reduce energy consumption in WMN without significantly impacting the network performance.

**Keywords** Wireless mesh networks · Energy conservation · Efficient · Energy management · Green routers · MILP · Performance evaluation

## 1 Introduction

Wireless networks have become an essential part of the modern life. However, recently, 3 % of the worldwide energy is consumed by ICT infrastructures, causing about 2 % of the worldwide CO<sub>2</sub> emissions. The volume of transmitted data increases rapidly and wireless communications are used extensively while network design rules have practically ignored the energy efficient network design approach to limit CO<sub>2</sub> emissions [1]. Therefore, the cost of energy is increasing continuously as well as the necessity for expanding the broadband services.

Green network has recently been proposed to reduce energy costs and carbon footprint of computer networks. Green networking consists of rethink how networks are constructed

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and operated so that not only the cost and performance are taken into consideration, but also their energy consumption and carbon footprint [2]. Green networking solution provides global environmental network architectures to improve energy efficiency, performance and reduce the cost savings. It also allows companies to gain competitive advantage and maintain a sustainable environment. However, the interest for the energy saving of the wireless infrastructure has only increased in recent years, given the explosion in applications of wireless Internet. Network devices connected to the Internet have a significant impact on energy costs. Considerably, access networks consume approximately 70 % of energy costs of global telecommunications networks and this percentage should increase over the next decade [3]. This is mainly because the wireless access networks (WANs) are generally dimensioned to meet the demands in terms of peak traffic constraints, resulting in over-provisioning in low-demand periods wasting a significant amount of power. In this respect, trying to minimize the energy consumption of deployed access elements is an important goal.

Applying of green networking to multi-hop wireless access networks, in particular Wireless Mesh Networks (WMNs) has been rarely reported in the literature. WMNs are a variant of Mobile Ad hoc Networks (MANETs), and are an IEEE 802.11-based infrastructure network [4]. They are now being used to deploy Wi-Fi coverage in a wide variety of outdoor applications. In these types of networks, conventional mesh nodes must be operated using continuous electrical power connections. This requirement may often be very expensive, especially when the network includes expansive outdoor wireless coverage areas. An alternative is to operate some of the mesh nodes using renewable energy sources such as solar or wind power. However, our recent consideration of such networks revealed that they are rarely used at their peak capacity besides the fact that the entire MRs remains active continuously [2]. Thus, during lower traffic periods the energy consumption is the same as in busy hours, while it would be possible to save a large amount of power putting underutilized MRs to the sleep state.

Solving such a problem of energy consumption uprising in WMNs, consists alternatively in introducing green routers that can harvest green energy (such as solar or wind energy). In addition to that, the flexibility of wireless mesh networks with the need to optimize energy consumption by getting the advantage of periods of low demand and dynamic reconfigurations that are possible in WMNs. This paper focuses primarily on the energy consumed by network devices, a high density of hundreds of thousands of mesh routers are most widely used and deployed around the world as part of the Internet infrastructure. The key objective of the proposed work is to optimize network energy consumption by putting under-utilized MRs (Electrical Power Supply Mesh Routers ACMR and Green Energy Supply Mesh Routers GMR) to

sleep state by following variation of traffic load and solar energy generation during the hour's intervals of the day. To do so, we first propose an optimal approach called Optimal Energy Efficiency Management Design (OEEMD) by formulating the problem as a Mixed Integer Linear Program (MILP) model to investigate the power consumption in WMN. As this problem is known to be NP-hard, we then propose an efficient heuristic algorithm called Green Energy Efficiency Management Design (GEEMD) for wireless mesh networks. GEEMD uses a sleep mechanism to power on/off underutilized MRs, based on the traffic load and solar energy generation. GEEMD uses a sleep mechanism to power on/off underutilized MRs, based on the traffic load and solar energy generation. For a performance evaluation, we used OEEMD and GEEMD to study the performance of WMN deployment scenario in the university and campus area of Tlemcen city in Algeria over dynamic traffic profiles. To the best of our knowledge, this is the first paper proposing a network energy management designed to optimize the energy consumption in WMNs with the two kinds of mesh routers (green and non green) such that traffic demands can be satisfied with a clean harvested energy of green mesh routers.

The rest of the paper is organized as follows. Section 2, reviews some related work on energy management in access networks that have been proposed to enable energy-efficiency. Section 3 describes the WMN architecture and techniques for energy-savings in WMN. Section 4 presents OEEMD problem formulation to optimize network energy consumption. In Section 5, we introduce heuristic algorithm of GEEMD for wireless mesh network. Section 6, we present a case study to illustrate the effectiveness of our work and illustrative numerical examples on the case study. Finally, we conclude in Section 7.

## 2 Related work

Despite of the fact that the cost of power continues to rise, and the necessity for providing broadband, green network has become one of the most important research areas of ICT industry.

Good overviews of the research on green networking and methodological classifications are given in [5–7] where different methods adopted in the literature for both wired and wireless networks are surveyed. Wireless networking community has developed several techniques for wireless technologies with high-energy efficiency. In the literature, different approaches have been proposed to reduce the power consumption in different kinds of access networks [8, 9]. A survey of energy-efficient protocols for wireless mesh networks can be found within [10].

Many proposals have been made in the literature, mainly in the context of wired networks. Authors in [3] develop an

energy-aware design technique and routing protocols in hybrid wireless-optical broadband access network (WOBAN) to reduce the number of used Optical Network Units (ONUs). They formulate the problem as an ILP for multi commodity flow and provide the optimal routing to reduce the number of used ONUs and enable energy savings in the optical part but not in wireless part, which is a wireless mesh network. While in [11], authors propose to turn off the nodes one by one and make sure that the network still routes the necessary traffic.

Pertinent works on energy efficiency are given in the context of WMNs [2, 12–16]. The authors in [2] try to minimize the energy in a time varying context by selecting dynamically a subset of mesh routers to switch on considering coverage issues of the service area, traffic routing, as well as capacity limitations both on the access segment and the wireless backhaul links. However, they do not take into consideration the interferences. Moreover, they concentrate just on the optimization of energy consumption without treating the issue of network throughput. The authors extended this work in [12] by introducing a joint planning and energy management framework for WMNs. They present a mathematical model considering a trade-off between capital and energy-related operational expenses. Authors in [13] consider energy-savings through optimized management of on/off state and transmission power of access stations according to traffic estimated in different hours of the day or days of the week. Another energy management study in WMNs is provided in [14], where a combination between different modulation techniques and power adaptation is presented. Specifically, authors in [15] propose a new framework for energy management in TDMA based WMNs to support energy efficient communications, which aims at finding an optimal trade-off between the achieved network throughput and energy consumption. To do so, they propose an optimal approach, which is formulated as an integer linear program (ILP). Then they propose a simple efficient Ant Colony-based approach to solve the formulated ILP problem. Through extensive simulations, green framework shows that it is able to achieve significant gains in terms of energy consumption as well as achieved network throughput. The authors extended this work in [16] and introduce an online flow-based routing approach in WMNs focusing 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.

The sustainability of energy has drawn a lot of attention in recent years for growing the energy consumption. Conventional approaches assume that all routers are constantly powered by electricity, and concentrate on the device configuration or routing schedules. Today, green routers supplied by renewable energies offer a cost effective alternative for network planning and the issue of energy is revisited in green wireless mesh networks. Certain work about how to extend

the life of rechargeable batteries properly configuring a solar panel to reduce the outage probability [17]. Some focus on energy-aware resource management and efficient routing scheduling. In [18] and [19], authors propose resource management schemes to evenly distribute traffic across the network so that the harvested energy can sustain the network operation. Another work in [20] shows the management strategies for energy savings in solar powered 802.11 WMNs. Specifically, in [21] authors study the problem of rechargeable router placement with QoS guarantees. They provide an energy flow model to characterize the energy charging and discharging process for a rechargeable router. Furthermore, they consider a time-varying traffic demand model for mobile users.

Contrary to the related works, our works exclusively with planning and network management while our goal is to manage the energy consumption of green WMNs. The presence of the wireless backbone requires us to optimize network energy consumption by reducing the number of used MRs and putting under-utilized MRs (Electrical Power Supply Mesh Routers -ACMR and Green Energy Supply Mesh Routers -GMR) to sleep state by following variation of traffic load and solar energy generation during the hour's intervals of the day.

### 3 Background

In this section, we present the architecture of WMNs and techniques for energy saving in WMNs.

#### 3.1 WMN architecture

As various wireless networks evolve into the next generation to provide better services, a key technology, wireless mesh networks (WMNs) have emerged [4], which are a variant of Mobile Ad hoc Networks (MANETs). They are an IEEE 802.11-based infrastructure network made up of Mesh Routers (MRs) and mesh clients (MCs), where mesh routers have a minimum mobility and form the backbone of WMNs. The integration of WMNs with other networks (the Internet, cellular, IEEE 802.11, IEEE 802.15, IEEE 802.16, sensor networks...) can be achieved through the gateway and bridging functions in the mesh routers. Clients mesh may either be fixed or mobile, and can form a client mesh network between themselves and with mesh routers as shown in Fig. 1.

In WMNs there are two types of mesh points: Mesh Routers (MRs) and Mesh Access Points (MAPs). The first one provides network access for the Mesh Clients (MCs) and forwards their messages to other routers through point to point wireless links, while the latter acts as routers as well as Internet gateway.

WMNs are currently being standardized under IEEE 802.11s, which intends to promote interoperability between

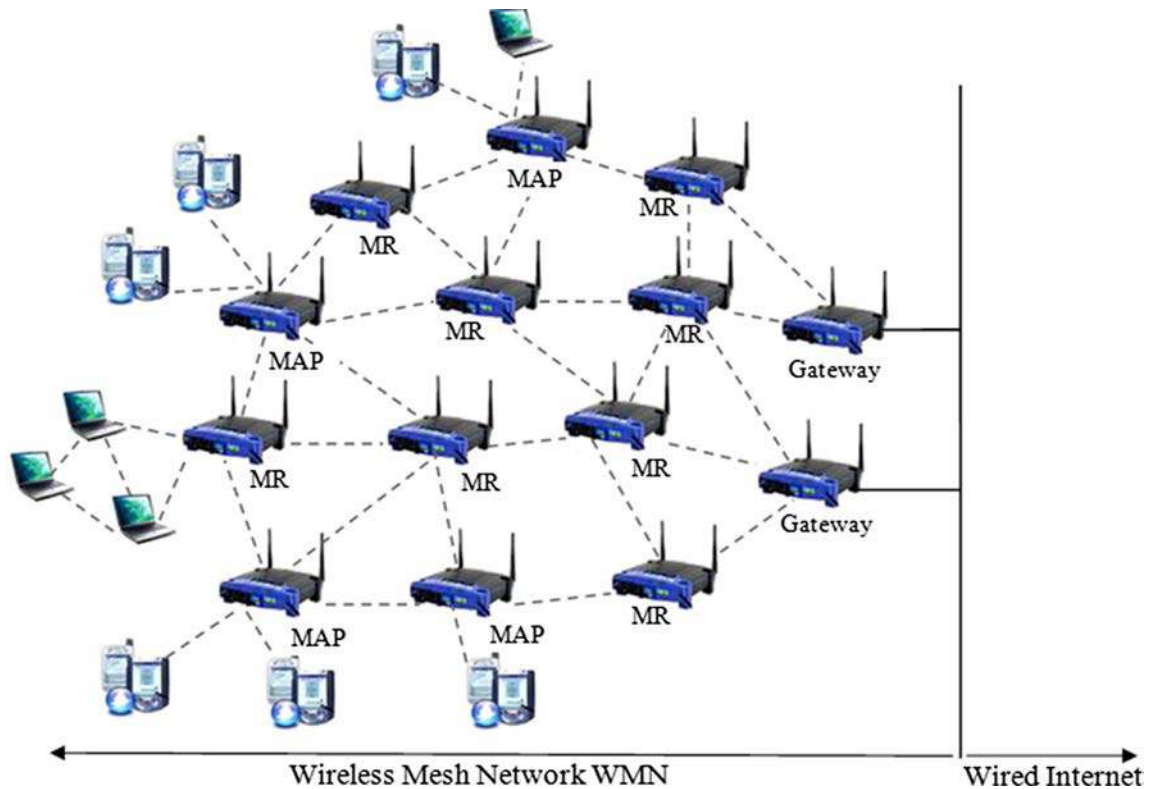


Fig. 1 Wireless mesh network architecture

different vendor solutions. One of the major costs of certain WLAN mesh deployments is that of providing MAPs/MPs with electrical power and wired network connections. This is especially true in Wi-Fi hot-zones, where coverage is provided over extended outdoor areas. Although power can be supplied through power over Ethernet (POE), such a solution requires a wired network connection, which is often very expensive. For the past several years, the SolarMESH network has been under development and undergoing deployment trials at McMaster University [18, 21]. In SolarMESH, APs are solar-powered and can be deployed quickly and inexpensively for outdoor Wi-Fi coverage in campuses, building complexes, and others Wi-Fi hot-zones.

However, WMNs infrastructure devices are always active. Thus, during lower traffic periods the energy consumption is the same as in busy hours, while it would be possible to save a large amount of power by turning off unnecessary nodes. Concerning this issue, a green energy efficiency management design for such kind of networks will be tackled in the next Section.

### 3.2 Energy savings in WMN

Various aspects of WMNs should be considered for its energy-aware design. Present conception of WMN, deployment and management approaches provide fault tolerance, reliability and robustness along with a high degree of performance. Thanks to the mesh backbone, where the traffic can be

rerouted through alternative paths in the case of failures such as the failure of a wireless router or gateway. At a specified moment, it is possible to find multiple WMN topologies that can meet the capacity requirements and reliability objectives. This is possible through the densely interconnected wireless mesh that has many redundant paths to send the traffic. The flexibility offered by the WMN can be exploited to allow energy savings.

A further significant feature of the access network is its traffic profile. The traffic load on the access network arriving directly from clients, and it is well known that there are daily fluctuations of this load. During WMN (as well as other network) deployment, the common practice to deploy network equipments so that they may support peak traffic load. Consequently, during low load hours, some parts of the network can be underutilized.

So, to design WMN topologies with reduced power consumption, we must take into consideration the following points: the advantage of the Green Routers that can be deployed quickly and inexpensively for outdoor Wi-Fi coverage; WMN topology may anticipate multiple redundant paths for a packet to reach its destination and the traffic load fluctuation during different hours of the day. Consequently, we can selectively put some nodes to sleep state during low load hours, thereby reducing network wide power consumption.

In WMN, we must hold all the wireless Mesh Routers MRs ON to make sure the availability of the network. In this paper,

our main focus is how to put MRs of WMN into sleep state. We will not discuss putting gateway into sleep state as it connects the WMN to the rest of the Internet. In this paper, we reduce the MRs power consumption in WMN by putting low load MR to sleep state.

## 4 OEEMD problem formulation

WMN represents hierarchical access architecture with routers as the original traffic aggregation points. Gateways are the highest aggregation point to access network with the rest of the Internet.

To achieve the above defined goal, we propose an optimal approach, called Optimal Energy Efficiency Management Design (OEEMD) by formulating the problem as a Mixed Integer Linear Program (MILP). As this problem is known to be NP-Hard, we then propose an efficient heuristic algorithm called Green Energy Efficiency Management Design (GEEMD), to solve the formulated MILP problem. Detailed descriptions of optimal approach are in the following section.

### 4.1 Network model

We represent a WMN by a directed graph  $G = \{V, E\}$ , called a connectivity graph, where: where  $V$  is the set of nodes and  $E$  is the set of wireless links. Where  $V$  has two subsets:  $V_G$ , is the subset of the Gateways provide the connectivity to the Internet and  $V_{MR}$  which is the subset of Mesh Routers MRs that contains two subsets (AC power supply Mesh Routers -  $V_{ACMR}$  and Green Mesh Routers -  $V_{GMR}$ ). Each node  $v_i \in V$  represents an AP with a circular transmission range  $R_T(i)$  and an interference range  $R_I(i)$ . During the transmission of the node  $v_i \in V$ , all the nodes residing in its transmission range receive the transmitted packet. The connectivity graph is fully defined by the connectivity matrix  $M$ ; a matrix with rows and columns labeled by the graph vertices  $V$ , with a 1 or 0 in position  $(i, j)$  according whether  $v_i$  and  $v_j$  are directly connected or not.  $C_{i,j}$  a variable expressing the capacity over a wireless link  $(i, j)$ .

### 4.2 Interference model

In this paper, we adopt the protocol interference model [16] in which a node  $v_j$  is interfered by the signal from  $v_i$  whether  $\|v_i - v_j\| \leq R_I(i)$  and  $v_j$  is not the intended receiver. Recall that  $\|v_i - v_j\|$  refers to the Euclidean distance between  $v_i$  and  $v_j$ . The transmission from  $v_i$  to  $v_j$  is viewed successful if  $\|v_k - v_j\| \leq R_T(k)$  for every node  $v_k$  transmitting in the same time.

We use the conflict graph  $F_G$  to represent the interference in  $G$ . Each vertex of  $F_G$  corresponds to a directed link  $(i, j)$  in the connectivity graph  $G$ . There is a directed edge from vertex  $(i, j)$  to vertex  $(p, q)$  in  $F_G$  if and only if the transmission of link  $(i, j)$

interferes with the reception of the receiving node of link  $(p, q)$ . The conflict graph  $F_G$  is then fully defined by the interference matrix  $I$  as follows:

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

### 4.3 Energy consumption model

In this work, a MRs can be in three different states: Active (i.e., Transmitting/Receiving), Idle and Off. Note that in the idle state, a MR is ON, but is neither transmitting nor receiving. As reported through the experimental measurements in [22], the power consumption of an Active MR represents the peak power consumption, and an Idle MR consumes almost 75 % of its peak power consumption. Finally, an Off MR does not consume any power.

In this paper, we adopt green energy, namely, solar power from natural environment. The harvested energy is dynamic and variable in different times of a day. Solar energy can be effectively used for power during the day. Energy requirements for the different business or universities consume during daylight hours, nearly 80 % of total consumption is encountered during daylight hours (Fig. 2). Based on field measurements of charged power for 24 h of a summer day in Algeria plotted in the Fig. 2, we derive a model of approximate charge consists of a quadratic curve and zero to model the energy harvested during the day and the night, respectively. We consider the same 1-day energy-charging model for green routers.

For the general comprehension of the problem, the typical power consumption by a MR during active state is approximately 15 W [2]. It is also estimated that, during sleep state, power consumed by a MR is less than 1 W [3]. The daily energy production varied quite a bit all through the year, depending on weather and day length. The peak production day this year was 25.5 kWh on June 18. The lowest day produced a mere 0.3 kWh on November 19. The daily average through the year was 11 kWh [23]. Therefore the solar energy harvested solar could be used adequately to supply the green router.

### 4.4 Problem formulation

The overall problem we are taken into account aims at managing network devices to save energy when a portion of network resources, namely MRs and links between them, are not required and can be deactivated. The key idea of this model is to determine which elements of the network should be turned OFF such that energy consumption is reduced and demanded is always satisfied. Now, we aim to find out the optimal number of Green Mesh Routers GMRs and conventional ACMRs

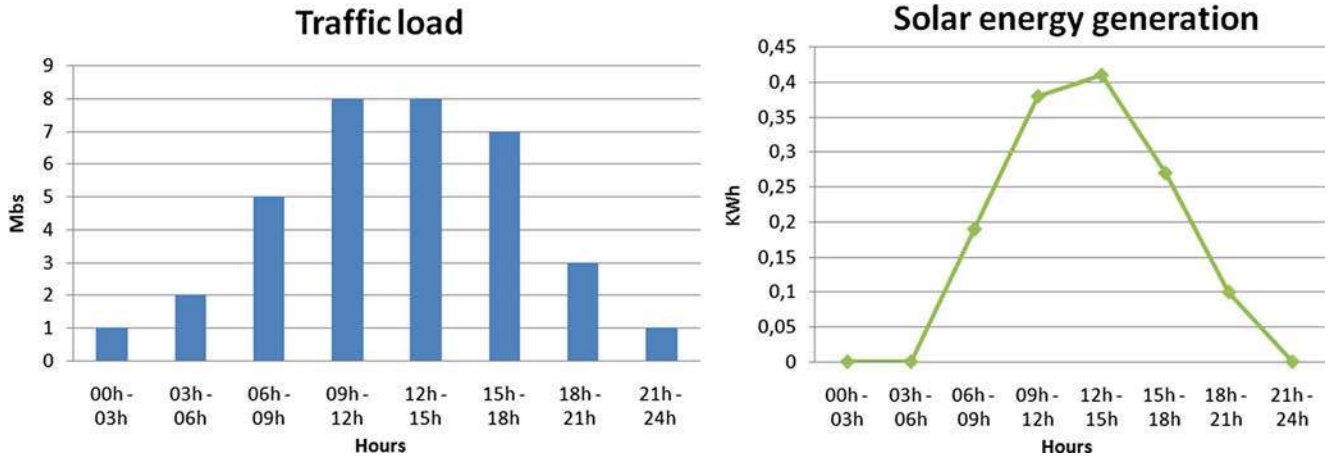


Fig. 2 Traffic profile, solar energy generation

needed to support a given amount of traffic load. This is a multi-commodity flow problem where each commodity represents the traffic flow between a source destination pair. We formulate the problem as a mixed integer linear program (MILP). We assume that the network has already been built, the conventional ACMRs and GMRs have been installed and the connectivity and traffic matrix is known in advance. Therefore, we propose the following mathematical notation.

*Our model takes as input:*

- A physical topology represented by the graph  $G = \{V, E\}$ , which is described by the connectivity and interference matrices  $M$  and  $I$ , respectively, and a set of Green Mesh Routers GMRs and conventional ACMRs
- Traffic load matrix  $T$  that contains the variation of traffic in throughout the day.

*The model generates the output:*

- Determines minimum number of Green Mesh Routers GMRs and conventional ACMRs that need to be kept active to route the given traffic load. The other MRs can be put to sleep state so that network-wide energy consumption is minimized.
- Find an optimal route for each flow from the source to the destination.

$X_i$  Binary variable denoting ACMR state,  $X_i \in \{0, 1\}$ . 0 denotes ACMR is a sleep, and 1 denotes ACMR is active.

$$X_i \in \{0, 1\} \begin{cases} 0 & \text{ACMR is sleeping} \\ 1 & \text{ACMR is active} \end{cases}$$

$$\text{ACMR is active if } \sum_{j \in V} (\gamma_{ij} + \gamma_{ji}) = 0 \forall i \in V$$

$Y_i$  Binary variable denoting Green GMR state,  $Y_i \in \{0, 1\}$ . 0 denotes GMR is a sleep, and 1 denotes GMR is active.

$$Y_i \in \{0, 1\} \begin{cases} 0 & \text{GMR is sleeping} \\ 1 & \text{GMR is active} \end{cases}$$

$$\text{GMR is active if } \sum_{j \in V} (\gamma_{ij} + \gamma_{ji}) = 0 \forall i \in V$$

$\gamma_{ij}$  Binary variable denoting the total flow on the link between  $i$  and  $j$ .

$$\gamma_{ij} \in \{0, 1\} \begin{cases} 1 & \text{If flow 1 is routed from } i \text{ to } j \\ 0 & \text{Otherwise} \end{cases}$$

Now, the objective function can be written as:

$$\text{Minimize} \left( \alpha \sum_{i \in V_{ACMR}} X_i + \beta \sum_{i \in V_{GMR}} Y_i \right) \quad (1)$$

The objective will be to minimize number of conventional ACMRs and Green Mesh Routers GMRs that need to be kept active to support the given traffic load. Where  $\alpha$  and  $\beta$  represent weighting coefficient for ACMR and GMR respectively. We adapt  $\alpha$  and  $\beta$  to different hours of day and give importance to the achieved energy saving by conventional routers and green routers

The optimization is subject to the following constraints (2)–(12):

$$\gamma_{ij} \geq M_{i,j} \quad \forall i, j \in V \quad (2)$$

$$\gamma_{ij} \leq C_{i,j} \quad \forall i, j \in V \quad (3)$$

$$\gamma_{ij} = 0 \quad \forall i, j \in V_G \quad (4)$$

$$\sum_{j \in V} \gamma_{ji} \leq 1, \sum_{j \in V} \gamma_{ij} \leq 1 \quad \forall i \in V_{MR} \quad (5)$$

$$\sum_{h \in V_{MR}} (\gamma_{hj} - \gamma_{jh}) + \sum_{i \in V_G} \gamma_{ij} T_{ij} = \sum_{i \in V_G} \gamma_{ij} \quad \forall j \in V_{MR} \quad (6)$$

$$\gamma_{i,j} + \gamma_{p,q} I_{(i,j),(p,q)} \leq 1 \quad \forall i, j, p, q \in V \quad (7)$$

$$\sum_{i \in V_{MR}} \sum_{j \in V_G} \gamma_{ij} = 1 \quad (8)$$

$$\sum_{j \in V} \gamma_{ij} + \sum_{j \in V} \gamma_{ji} \leq \sum_{j \in V} X_j / m \quad \forall i \in V_{ACMR} \quad (9)$$

$$\sum_{j \in V} \gamma_{ij} + \sum_{j \in V} \gamma_{ji} \leq \sum_{j \in V} Y_j / m \quad \forall i \in V_{GMR} \quad (10)$$

$$\sum_{j \in V} \gamma_{ij} \leq H \quad \forall i \in V \quad (11)$$

$$X_i, Y_i, \gamma_{ij} \in \{0, 1\} \quad \forall i, j \in V \quad (12)$$

Constraint in Eq. (2) ensures that no transmitting over a non-existing link. Constraint in Eq. (3) represents the link capacity condition on the total flow through a link. Constraint in Eq. (4) ensures that traffic is not routed after reaching a gateway node. This means that the gateways are assumed to have enough capacity to send all the received traffic toward the Internet. Constraint in Eq. (5) avoids loops while routing a flow. Constraint in Eq. (6) makes reference to the flow continuity constraint, which guarantees the routed path to be continuous. It ensures that all the incoming flows are routed in addition to the flows originating from the node. Constraint in Eq. (7) implies 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. Constraint in Eq. (8): ensures that all the flows are successfully routed to one of the available gateways. Constraint in Eqs. (9) and (10) determines the ACMR and GMR state. If some traffic flows  $\gamma_{ij}$  through an  $ACMR_i$  or  $GMR_i$  it should be active, otherwise it should be in sleep state where  $m$  is a very large value used to map (i.e., to normalize) the flow variables into a binary variable  $X_i, Y_i$ . This constraint in Eq. (11) put a limit on the path length. Each flow path should not be longer than  $H$  hops. The last Constraint in Eq. (12) indicates that  $X_i, Y_i$  and  $\gamma_{ij}$  are binary variables.

This formulation turns out to be an MILP as some variables can take non integral values. This specific MILP formulation is a NP-Hard problem [24]. It requires huge computation capacities to find the best solution. We give in Eq. (13) the complexity of exhaustive solution to show the number of possible combinations to solve it. The fact that the key objective of the proposed work is to optimize network energy consumption by putting under-utilized MRs (Electrical Power Supply Mesh Routers ACMR and Green Energy Supply Mesh Routers GMR) to sleep state by following variation of traffic load and solar energy generation during the hour's intervals of the day.

Therefore, we need to find the optimal number of  $k$  ACMR from  $m$  possible initial number of ACMR ( $k \leq m$ ) and  $h$  GMR from  $n$  possible initial number of GMR ( $h \leq n$ ). We can write it as mathematic combinations  $C_m^k + C_n^h$ . However,  $k$  and  $h$  is

unknown and it is in the interval  $\{1 \dots m\}$  and  $\{1 \dots n\}$  respectively. Consequently, the problem complexity becomes

$$\sum_{k=1}^m C_m^k + \sum_{h=1}^n C_n^h. \quad (13)$$

Due to the problem complexity with the heavy computation required and the large number of variables and constraints of the network, we propose to use a heuristic to solve it in order to reduce the resolution computation time and get the best solution. We try to solve our model with smaller networks to verify the correctness of our problem formulation. For solving MILP, we use ILOG CPLEX [25] on Intel Core 2 Duo machine with 4 Gigabyte RAM. We use a small 22 node WMN with 10 green routers, 10 conventional routers and 2 gateways. However, sophisticated heuristics can be used to solve it in a reasonable amount of time. The number of design variables in this problem is not exceptionally large. But for a very large numbers of nodes, the problem becomes quite large. However, WMN with a larger number of nodes and mode traffic load, we need to construct heuristics to solve this problem. We propose a heuristic on the selection of MRs to turns OFF in the next section.

## 5 Green energy efficiency management design

In this section, we present the Mesh Router (ACMR/GMR) Sleep Algorithm of Green Energy Efficiency Management Design for wireless mesh network to reduce network energy consumption.

### 5.1 GEEMD problem statement

A general problem that we are considering aims to manage the mesh nodes in order to conserve energy when some of the nodes in the network are not required and can be deactivated. Energy efficiency is therefore calculated to be the number of nodes that may be turned off without compromising the network performance. This model of energy conservation is called ON-OFF model, was first introduced by Restrepo et al. [26] and reused in the context of wireless networks in [27, 28]. General knowledge about how the effectiveness of the energy could be reached in WMNs has been introduced in [5], like turning off nodes, the transmission power control and rate adaptation. However, no details about how such techniques may be effective are specified. From an operational point of view, this may be easily integrated in centralized network management platforms currently used for carrier grade WMNs and to the centralized and remote control of all devices and their configuration [29].

Wireless mesh networks (WMNs) are dynamically self-organized and self-configured, with the nodes in the network automatically establishing an ad hoc network and maintaining



the mesh connectivity. Multiple paths are selected between source and destination. When there is a sleeping mesh router on a path, another path in the set of existing paths can be chosen. Thus, without waiting to set up a new routing path, the end-to-end delay, throughput, and fault tolerance can be improved [4]. Several aspects of WMN need to be considered for its Green Energy Efficiency Management Design. Current WMN design, deployment, and management methods provide fault tolerance, reliability, and robustness as well as a high level of performance. Thanks to the mesh features, where the traffic can be rerouted through alternate paths in case of failures such as a failure of a wireless router or gateway. The redundant capacity in the mesh backhaul can provide extra reliability during the failure so that traffic can be rerouted through alternate paths. At a specific instant, it is possible to find several WMN topologies that can satisfy the required capacity and reliability objectives. All these are possible due to the densely-interconnected wireless mesh which has many redundant paths to route traffic. The flexibility provided by the wireless mesh can be exploited to enable energy savings.

Infrastructure devices in WMNs remain active during the whole day; the energy consumption is constantly high, while it would be possible to save a large amount of power by switching off unneeded nodes during low traffic periods. To this end in [2], starting from a deployed network, an optimization model is proposed for dynamically selecting a subset of routers and access points to be turned ON following the traffic variations; even so, energy management is still considered as an exclusively operational feature. Differently, here we aim at demonstrating that, given the highly adaptive features of the mesh architecture that includes green and conventional nodes, an energy management approach can provide further energy efficiency improvements using the sleep mechanism described in Algorithm.1.

**Algorithm 1 Mesh Router (ACMR/GMR) Sleep Algorithm**

Input: WMN topology, ACMRs, GMRs, Low Traffic (LT), Means Traffic (MT) and High Traffic (HT), Weight coefficient  $\alpha$  (ACMR) and  $\beta$  (GMR), T hour's intervals.

Output: Set of ACMRs or GMRs that can be put to sleep state.

- **Initialization:** Initialize LT, MT, HT,  $\alpha$  and  $\beta$ .

- **Measurement:** At different hour's intervals of the day, the centralized management quantifies traffic load at different MRs and estimates the amount of solar energy generation.

- **Decision: MRs (ACMR/GMR),**

- If  $\alpha = \beta = 1$ ,  $T \in [00h-03h]$  &  $T \in [21h-24h]$

- If  $load < LT$ , put to sleep state ACMR and GMR.

- else if  $load > MT$ , keep ACMR/GMR active.

- else if  $load > HT$ , keep ACMR/GMR active

and turn ON inactive (ACMR or GMR).

- If  $\alpha > \beta$ ,  $T \in [03h-06h]$

- If  $load < LT$ , put to sleep state GMR.

- else if  $load > MT$ , keep GMR active.

- else if  $load > HT$ , keep GMR active and turn ON inactive ACMR.

- If  $\alpha < \beta$ ,  $T \in [06h-21h]$

- If  $load < LT$ , put to sleep state ACMR.

- else if  $load > MT$ , keep ACMR active.

- else if  $load > HT$ , keep ACMR active and turn ON inactive GMR

In WMN, the centralized network management platform can manage centralized sleeping mechanism and maintain three different traffic profiles Low Traffic (LT), Means Traffic (MT) and High Traffic (HT). During different hours of the day, the centralized network management platform will observe the traffic load at different MRs (ACMRs/GMRs) by measuring the length of corresponding input queues and estimates the amount of solar energy generation following the scheme of solar energy generation Fig. 2. If  $\alpha = \beta = 1$  (the weight factor is equitable for each ACMR and GMR; this is true, during the night times interval where there is no generation of solar energy), we reduce the number of GMR and ACMR by following their traffic load. If an ACMR or GMR is operating under low traffic (LT), put it to sleep and the wireless mesh backbone will reroute the affected traffic to alternate paths due to ACMR or GMR shut-down. Otherwise keep ACMR or GMR active when traffic load increases above means traffic (MT) and put back the nearest sleeping ACMR or GMR into active state when traffic load increases above high traffic (HT). If  $\alpha > \beta$  (the weight factor of ACMR is higher than the weight factor of GMR; it is during sunrise where solar energy generation begin to increase but it is not sufficient), we are forced to reduce the number of GMR by following their traffic load. If GMR is operating under low traffic (LT), put GMR to sleep and the wireless mesh backbone will reroute the affected traffic to alternate paths. Otherwise keeps GMR active when traffic load increases above means traffic (MT) and put back sleeping ACMR into active state when traffic load increases above high traffic (HT). Finally, if  $\alpha < \beta$  (the weight factor of GMR is higher than the weight factor of ACMR; it is during sunshine where energy solar generation is high and gives priority to GMR), we reduce the number of ACMR by following their traffic load. If ACMR is operating under low traffic (LT), put ACMR to sleep and the wireless mesh backbone will reroute the affected traffic to alternate paths. Otherwise keeps ACMR active when traffic load increases above means traffic (MT) and put back sleeping GMR into active state when traffic load increases above high traffic (HT).

## 6 Case study and performance evaluation

In this section, we evaluate the efficiency of our proposed Green Energy Efficiency Management Design for wireless mesh network to reduce network energy consumption.

WMN deployment scenario shown in Fig. 3 is the hypothetical topology in the town of Tlemcen, which is a small city in Northern Algeria. The selected part of Tlemcen city has two different areas: 1) University area and 2) Campus area. These areas are chosen because they are situated in the biggest university center in Tlemcen and also they have a good user flow technology. In this work we took just a part to demonstrate the use of energy saving on our model. We can show the case of how profile traffic varies across different parts of the network, and also depending on the traffic profile during different times of the day, how we can set nodes to sleep. It can be shown, how profile of the traffic varies according to different parts of the network, and also according to the traffic profile during different times of the day, as well as the variation of solar energy generation, and how we can put MRs to sleep state.

The Wireless Mesh Network consists of hypothetical network deployment in two areas mainly the University and Campus area. So the total number of deployed Mesh Routers MRs is 100 with 12 gateways. Where we use two types of MRs, conventional routers with AC power called ACMR and Green Mesh Routers with green energy (solar energy) called GMRs. The University has 60 mesh routers with two kinds of MRs and 7 Gateways. The Campus area has 40 routers, with two kinds of MRs and 5 Gateways. The routers are equipped with one radio with a capacity of 54 Mbps (IEEE 802.11 g). Average distance between wireless routers is 250 m. It is based on the transmission range  $R_T$  and the interference range  $R_I=1,5 * R_T$ , and both the connectivity and conflict graphs are derived. In our simulations, we considered different traffic loads: Low Traffic 25 %, Means Traffic 50 %, and High Traffic 75 % in different hour's interval of the day to show the impact of network load on the evaluated metrics. Traffic sources are chosen randomly among MRs. In addition, we vary the weighting coefficient  $\alpha$  and  $\beta$  to determine the good tradeoffs between energy consumption by conventional MRs (ACMRs) and energy consumption by Green MRS (GMRs).

### 6.1 Traffic modelling

For our illustrative examples, we need to develop reasonable traffic profiles of the deployment areas during different hours of the day. Access networks deal directly with the user-generated Internet traffic. So, the behaviour of end-users has a significant impact on the performance of the access network. By following the access network traffic models in [18–20], we develop a traffic profile for each of the two different areas of

Tlemcen city. Each of these areas has different types of Internet users with different behaviour patterns and different peak usage periods.

We divide the 24 h of a day into eight intervals: interval 1: [00–03 h], interval 2: [03–06 h], interval 3: [06–09 h], interval 4: [09–12 h], interval 5: [12–15 h], interval 6: [15–18 h], interval 7: [18–21 h], interval 8: [21–24 h]. Period 1 begins at 00.01 AM in the morning. Figure 4 shows such a traffic profile for University and Campus of Tlemcen. We considered different traffic loads in different hour's interval of the day: In Campus Area: Low Traffic for the two first intervals ([00–03 h] and [03–06 h]), and Means Traffic for the intervals ([06–09 h], [09–12 h], [12–15 h] and [15–18 h]) and High Traffic for the two last intervals ([18–21 h] and [21–24 h]). In University Area: Low Traffic for the two first intervals and the last interval ([00–03 h], [03–06 h] and [21–24 h]), and High Traffic for the intervals ([06–09 h], [09–12 h], [12–15 h] and [15–18 h]) and Means Traffic for interval [18–21 h].

In this paper, we adopt green energy, namely, solar power from natural environment and the harvested energy is dynamic and variable in different times of a day. The total generation of solar energy is encountered especially during daylight hours and nearly 80 % of total traffic load is meeting during daylight hours. Figure 5 represents the variation of weighting coefficient  $\alpha$  (ACMR) and  $\beta$  (GMR) in different hour's interval of the day. To meet a good adaptation of  $\alpha$  and  $\beta$ : On one hand, during the nighttimes (interval [00–03 h] and [21–24 h]), we choose  $\alpha=\beta=1$ : we give equitable weight factor for each ACMR and GMR, to further minimize the number of ACMR and GMR as there is no light and no generation of energy during the night we reduce even the number of GMR and save their energy; On the other hand, during the daytime (interval [03–06 h], [06–09 h], [09–12 h], [12–15 h], [15–18 h] and [18–21 h]), we try to weight factors' weight  $\alpha$  and  $\beta$  relative to interval of the day and the amount of energy generated by the solar energy. Furthermore, when the amount of solar energy generated increases, even the weight factor  $\beta$  will increase as well, and that means that we try to use more GMR and we try to minimize the number of ACMR to save electrical power supplying. Alternatively, when the amount of solar energy generated decreases the weight factor  $\beta$  decreases too, it means that we try to use optimal number ACMR and we try to minimize the number of GMR to save their energy. All this is to determine the good trade-off between energy consumption by conventional MRs (ACMRs) and energy consumption by Green MRS (GMRs).

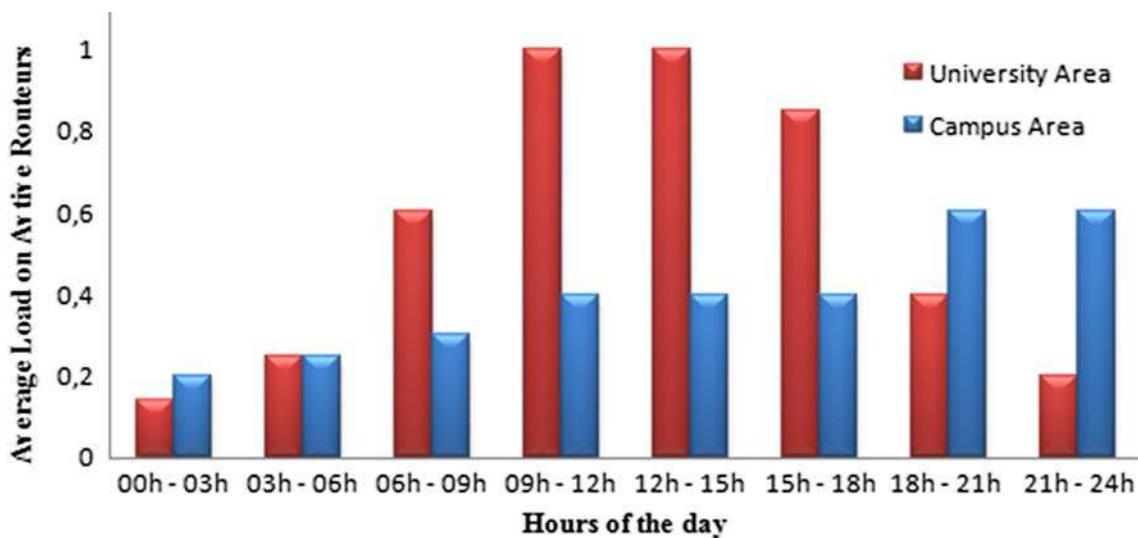
We evaluate the efficiency of our proposed GEEMD. The metrics used in our simulations concern the number of active Mesh Routers in University Area and Campus Area where the traffic load is not the same, the percentage of energy consumption by ACMR and GMR. Finally, we compare the energy savings produced by the two kinds of MRs. The reported results are obtained using Java™ implementation.

**Fig. 3** The hypothetical WMN deployment in Tlemcen City in Algeria



Figure 6 illustrates the number of active ACMRs and GMRs in University Area of Tlemcen during different hours of the day with different traffic load and various weighting coefficient  $\alpha$  (ACMR) and  $\beta$  (GMR). We can see that there is a daily

fluctuation in the traffic load and it is higher compared to the traffic load of Campus Area. During the morning hours (interval [06–09 h], [09–12 h], [12–15 h] and [15–18 h]) the traffic load is high in University Area and it is in accordance with the highest



**Fig. 4** The traffic profile of Tlemcen University and Campus areas

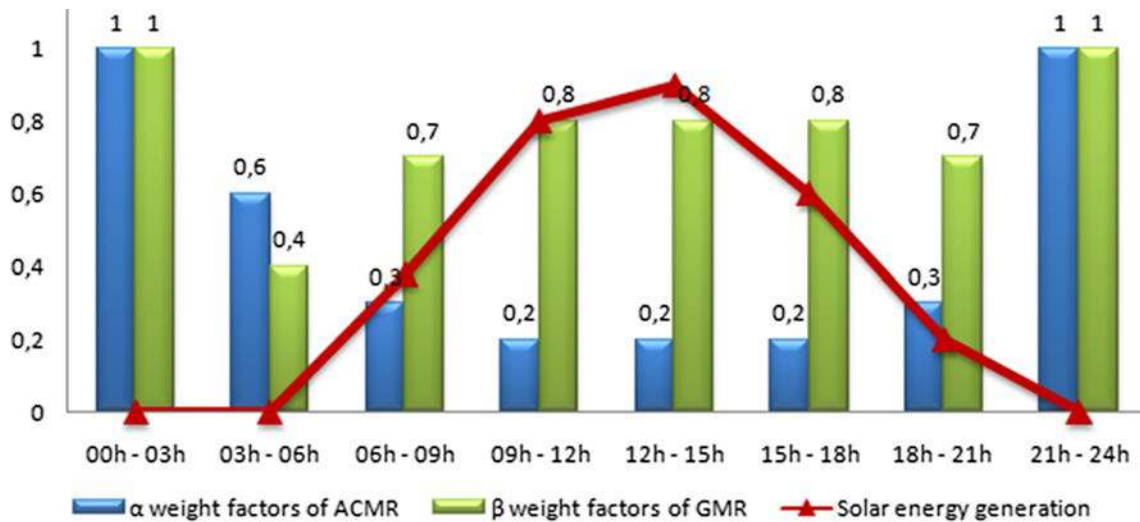


Fig. 5 The variation of weighting coefficient  $\alpha$  and  $\beta$  in different hour's interval of the day

rate of solar energy generation. As a result, we can see that the numbers of active GMRs is higher than the number of ACMRs. Due to the high rate of solar energy generation the weighting coefficient  $\beta$  (GMR) has more important weight than  $\alpha$  (ACMR). During the night (interval [00–03 h] and [21–24 h]) the traffic load is low in University Area and it is in agreement with the lowest rate of solar energy generation. Therefore, we can note that the numbers of active ACMRs is equal to the number of GMRs. According to the low rate of solar energy generation, we give equitable weight factor for each ACMR and GMR, to further minimize the number of ACMR and GMR as there is no solar energy generation during the night. During sunrise or sunset (interval [03–06 h] and [18–21 h]) traffic load is mean in University Area. In this case it is necessary to adapt the weighting coefficient  $\alpha$  (ACMR) and  $\beta$  (GMR) to meet the good trade-off between energy consumption by ACMRs and GMRs. during sunrise where solar energy production is low, we can see that the number of active ACMRs is superior to GMRs. Due to a greater weighting coefficient assigned to

ACMRs. During sunset where solar energy production begins to decrease, we can see that the number of active GMRs is higher the number of active ACMRs. Due to a greater weighting coefficient assign to GMRs.

Figure 7 illustrates the number of active ACMRs and GMRs in Campus Area of Tlemcen during the different hours of the day with different traffic load and various weighting coefficient  $\alpha$  (ACMR) and  $\beta$  (GMR). We can see that there is a daily fluctuation in the traffic load and it is less important than the University traffic load. During the morning hours (interval [06–09 h], [09–12 h], [12–15 h] and [15–18 h]) the traffic load is meant in Campus Area and the rate of solar energy generation is high. As a result, we can see that the number of active GMRs is higher than the number of ACMRs. Because of the weighting coefficient  $\beta$  (GMR) has more important weight than  $\alpha$  (ACMR). Furthermore, during the night (interval [18–21 h] and [21–24 h]) the traffic load is high in Campus Area and the rate of solar energy generation is low. Therefore, we can note that the number of active ACMRs

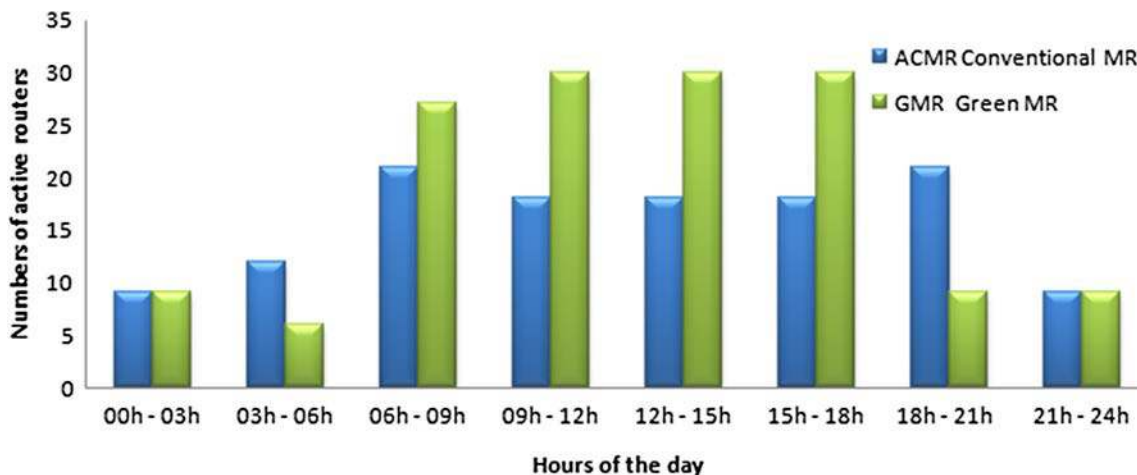


Fig. 6 Numbers of active mesh routers in University Area (total ACMR: 30, GMR: 30)

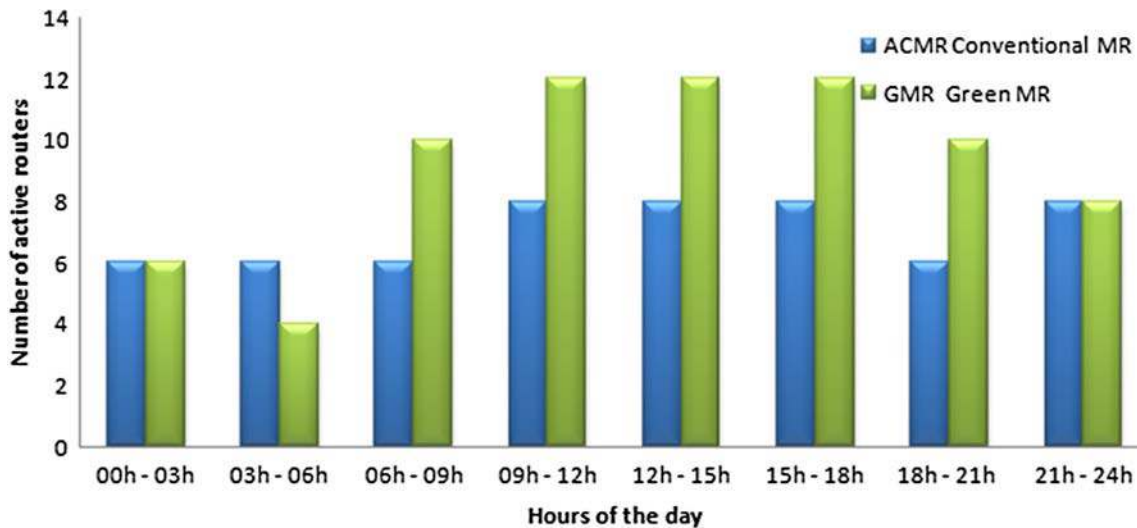


Fig. 7 Numbers of active Mesh routers in Campus Area (total ACMR: 20, GMR: 20)

is equal to the number of GMRs, in which, we give equitable weight factor for each ACMR and GMR and we try to minimize the number of ACMR and GMR. Consequently, we reduce even the number of GMR to conserve their energy. Therefore, during interval of low load we can reduce a lot of MRs by putting the MRs with low load in sleep state resulting in large energy conservation.

Figures 6 and 7 present the number of active ACMRs and GMRs in University and Campus Area where traffic load is different in these two Areas. During WMN deployment, the common practice is deploying MRs so that they may support the peak traffic load as in Campus Area. Consequently, during low load hours, some parts of the network can be underutilized. So, during intervals of low load we can reduce the numbers of ACMRs and GMRs by setting the ACMRs and GMRs with low load in sleep state. When the most part of

routers are active, we will not be able to put all ACMRs and GMRs to sleep. When a part of the network is highly loaded, for example the University Area and the Campus Area may be low load. We can save energy by putting the ACMRs and GMRs in Campus Area with low load to sleep state.

Figures 8 and 9 show the energy consumption (in terms of percentage of active MRs) during various periods of the day in the two areas of Tlemcen city. We compared the regular mode where all MRs are active with our Green Energy Efficiency Management Design; we can see that during the morning hours, the rate of solar energy generation is high. As a result, we can see that the number of active GMRs is higher than the number of ACMRs. Our choice focused on reducing the number of ACMRs, which are powered by electricity with the reduction of their energy consumption and CO<sub>2</sub> emissions. Thus, keeping more number of active GMRs powered by solar

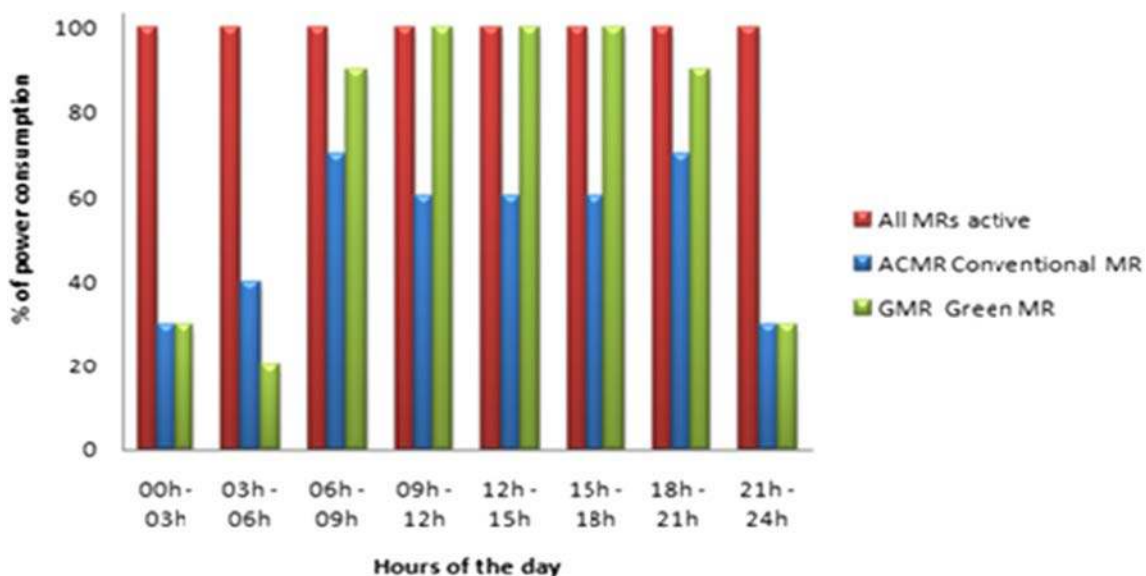
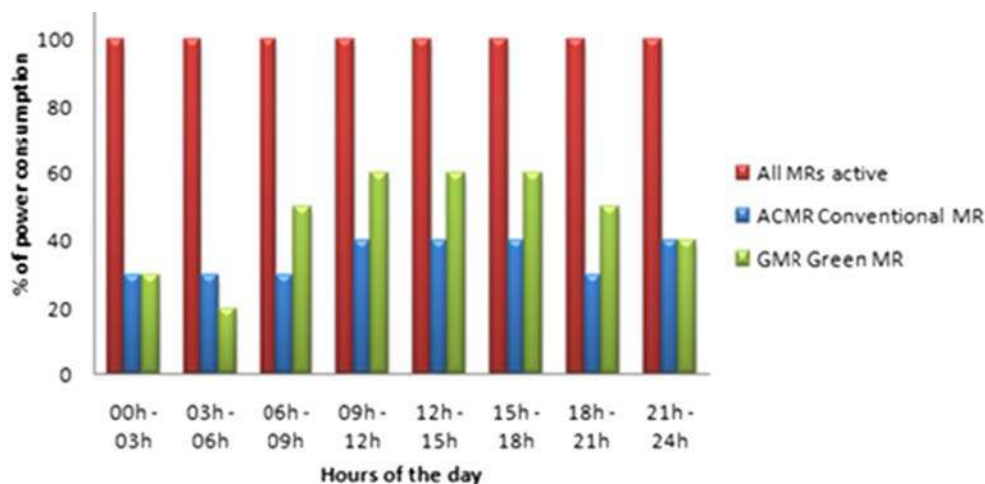


Fig. 8 The percentage of power consumption of active mesh routers in University Area

**Fig. 9** The percentage of power consumption of active mesh routers in Campus Area

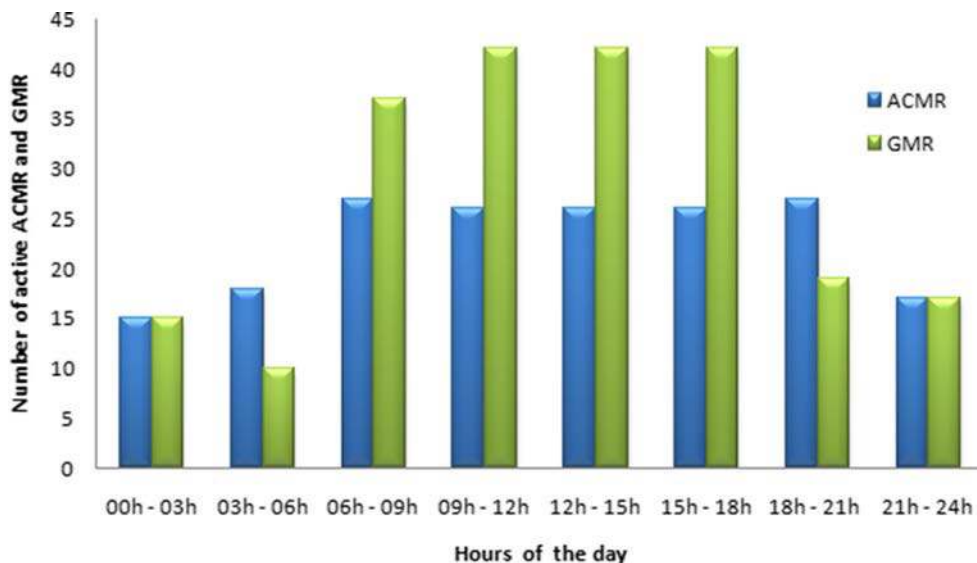


energy, which is inexhaustible and clean energy consequently, green energy is good to the environment. During the night the rate of solar energy generation is low. Therefore, we can note that the numbers of active ACMRs is equal to the number of GMRs. According to the low rate of solar energy generation, we give equitable weight factor for each ACMR and GMR, to further minimize the number of ACMR and GMR as there is no solar energy generation during the night. Consequently, we reduce even the number of GMR to conserve their energy for other functional period. During sunrise or sunset the rate of solar energy generation is proportional to the day interval. In this case it is necessary to adapt the weighting coefficient  $\alpha$  (ACMR) and  $\beta$  (GMR) to meet the good trade-off between energy consumption by ACMRs and GMRs. during sunrise where solar energy production is low, we can see that the number of active ACMRs is superior to GMRs. We use more ACMRs and we conserve energy of GMRs. During sunset where solar energy production begins to decrease, we can

see that the number of active GMRs is higher than the number of active ACMRs. Here we use more GMRs operating on green energy and save electrical energy of ACMRs.

Clearly, there is no energy saving in the regular mode where all MRs are active and energy consumption is maximal. Interestingly, in University Area we can put 50 % of the ACMRs to sleep state in our hypothetical deployment and save their energy consumption and use 70 % of GMRs with green energy. While in Campus Area we can put 70 % of ACMRs to the sleep state due to low load and use 50 % of GMRs. Arguably that if we can put 50 % and 70 % of ACMRs to sleep, why do we deploy them in the first place? The answer is because at high load, when all the routers are active, we will not be able to put any MR to sleep. The energy saving opportunity is somewhere else in the traffic profile. When one part of the network is at high load, the other parts may be in low load. We can save energy by putting MRs in those low-load parts to sleep.

**Fig. 10** Total numbers of active ACMR / GMR in University and Campus Area (total ACMR: 50, GMR: 50)



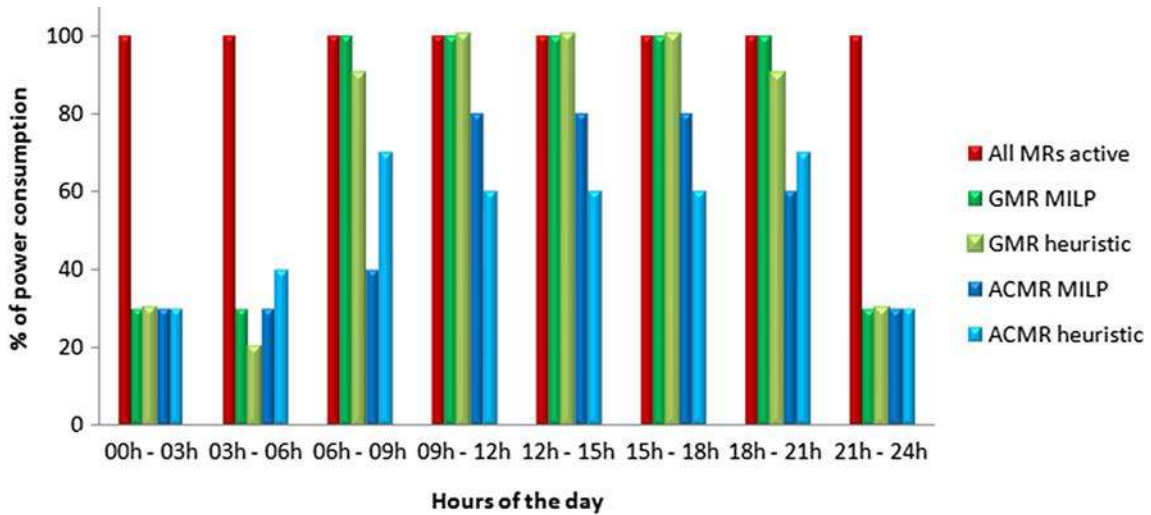


Fig. 11 Numbers of active mesh routers in small network (total ACMR: 10, GMR: 10)

Figure 10 shows the total numbers of active ACMR / GMR in University and Campus Area. In our hypothetical deployment Green Energy Efficiency Management Design uses 70 % of GMRs, which are powered with green energy and put 50 % of ACMRs to sleep state to conserve their energy. It results in considerable energy saving. Without forgetting to clarify that the university is equipped with 2600 MRs deployed in all area and we only took a part section to prove the energy saving that can have with Green Energy Efficiency Management Design.

## 6.2 MILP versus heuristics

So far, we have presented results from our heuristic method. To validate the effectiveness of the heuristic, we compare the results obtained from the MILP and the heuristic method. The MILP is not able to produce optimization results for a large WMN (such as the one in Fig. 3) in a reasonable amount of

time. We use a moderate 22 nodes WMN with 10 green routers, 10 conventional routers and 2 gateways for this comparison. The traffic profile and node distribution in area are similar to the ones in the previous Section. In this network, the MILP can be solved in a reasonable amount of time. For solving the MILP, we use the solver ILOG CPLEX [24] on Intel Core 2 Duo machine with 4 Gigabyte RAM. However, in the MILP, there is no limit on traffic load, so only MRs not carrying any traffic will be shutdown. The heuristic method closely follows the MILP results in number of active MRs and energy savings (Figs. 11 and 12). The reason is, similar to MILP, the heuristic method also tries to minimize energy consumption by putting MRs to sleep state following the traffic variations and energy solar generation.

The heuristic method provides a number of active routers slightly lower compared to MILP. Hence, we can deploy these heuristics to obtain near-optimal performance in wireless mesh network.

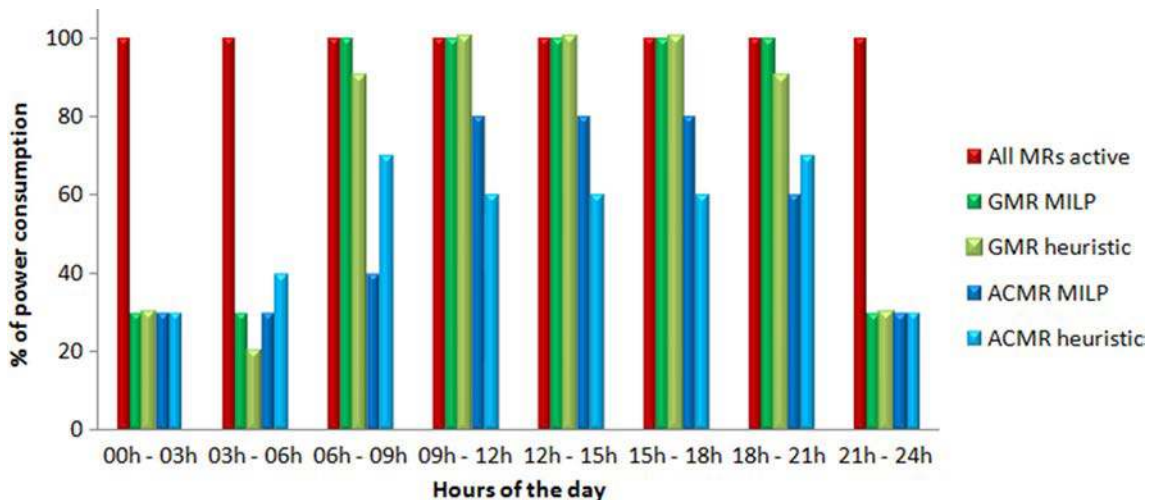


Fig. 12 The percentage of power consumption of active mesh routers in small network

## 7 Conclusion

In this paper, we draw attention that a large part of idle MRs results in considerable energy losses. Thousands of WMNs worldwide jointly aggravate this problem, while raising serious worry about the energy wastage that will happen in the future. In response to this problem, we first propose an optimal approach called Optimal Energy Efficiency Management Design (OEEMD) by formulating the problem as a Mixed Integer Linear Program (MILP) and developed a model that can act as a guideline on designing green WMN. As this problem is known to be NP-hard, we then propose an efficient heuristic algorithm called Green Energy Efficiency Management Design (GEEMD) for wireless mesh networks. The key objective of the proposed work is to optimize network energy consumption by putting under-utilized MRs (Electrical Power Supply Mesh Routers ACMR and Green Energy Supply Mesh Routers GMR) to sleep state by following variation of traffic load and solar energy generation during the hour's intervals of the day. For the performance evaluation, we used OEEMD and GEEMD to study the performance of WMN deployment scenario in the university and campus area of Tlemcen city in Algeria over dynamic traffic profiles. Both approaches are used to set and find a good compromise between solar energy generation and energy consumption using a parameterized objective function. Through extensive simulations, illustrative numerical examples show that, with suitable design parameters, GEEMD achieves significant gains in terms of energy consumption; we demonstrated it can be easily implemented. We conclude that the Green Energy Efficiency Management Design techniques applied on WMN can be generalized so that they are also applicable to other access networks. Our next step is to evaluate the performance of GEEMD with the dartmouth/campus dataset of CRAWDDAD that provides real localization of APs of the Dartmouth campus [30]. The most important message of this paper is that the energy wasted in large-scale and high-density WMNs is a new and serious preoccupation. This paper proposes the first attempt at designing green strategies to reduce energy wastage in WMNs. However, additional work is still needed to avoid the energy wastage and CO<sub>2</sub> emissions in the future.

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- and TPC co-chair of VehiCom2009 Workshop. He was the founding Chair of Ubiroads2007 workshop. He was the guest editor of a special issue of UBICC journal and was the special track co-chair in PIMRC'08 on ITS. He is founding co-editor of the IEEE ComSoc Ad Hoc and Sensor Network Technical Committee (AHSN TC) Newsletter. He also acted or still acts as TPC member of the following IFIP, ACM or IEEE conferences and workshops (ICC, GLOBECOM, PIMRC, GIIS, VTC, WiVeC, MWCN, IWWAN, Wireless Days, WITS,...). He is the Chair of IEEE ComSoc IIN Technical Committee, TCIIN (2014-2016). He is also a Member of IEEE and the Communications Society and Expert Senior of the French society SEE (Society of Electricity and Electronics).