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Energy-Aware Gateway Placement in Green Wireless Mesh Networks

Usman Ashraf

在满足业务流需求的情况下，最小化全局能量消耗。

***Abstract*—In this paper, we address the following problem: given a mesh network deployment and $|\mathbb{G}|$ gateways to be added, what is the optimal gateway placement with the constraint of energy-minimization for green wireless mesh networks. Unlike previous research, which focuses on throughput optimization, we contribute by developing a Mixed-Integer Linear Programming formulation which satisfies the given flow demands while minimizing the global energy consumption of the network. The proposed solution is NP-Hard, therefore we also propose a heuristic-based greedy algorithm to efficiently solve large instances of this problem. To capture interference in the mesh network, we use the physical-interference model but employ a greedy algorithm to reduce the computation time for finding Maximal Independent Sets (MIS). We implement both the MILP formulation and the greedy solution along with three other contemporary solutions in the area. Numerical results show that the proposed exact scheme provides the optimal result while the greedy solution provides a solution within 5% of the optimal solution with just 1% computation time for green wireless mesh networks.**

I. Introduction

OPTIMAL gateway placement can play a key role in the overall power-optimization of wireless mesh networks as gateways are the ingress and egress points for most of the network traffic. Gateway placement schemes [1][2] for wireless mesh networks primarily focus on network capacity maximization. A number of solutions exist on energy-efficiency in wireless mesh networks [3][4][5][6][7][8][9]. Most existing solutions [3][4][5][7][10] assume a given mesh deployment (including gateways) and perform simplistic energy-optimization by turning off nodes (or radios). These solutions are complementary to our work, since we focus on energy-efficient gateway placement based on long-term flow demands and assume a comprehensive energy model. In [3], authors minimize energy consumption by turning off radios while meeting demands, but assume a protocol interference model, ignore other factors of energy consumption and gateway placement. In [4] authors put to sleep, under-utilized nodes based on traffic patterns and solar power generation for green mesh routers, but do not consider gateway placement or interference constraints. In [5] and [11] authors propose energy-efficient solutions for battery-powered mesh networks, but do not consider gateway placement. In [10] authors formulate the problem of network-wide energy consumption as a nonlinear program by jointly optimizing routing, rate control, and power allocation. Other solutions assume a TDMA-based mesh network [7].

In [8], authors first develop an ILP for minimum-cost network deployment without concern to energy-efficiency, while we propose energy-efficient gateway placement. Next they propose an energy optimization model by turning off unused Base Stations based on changing traffic patterns. Authors assume directional antennas and no interference, while we assume a physical interference model (and propose a greedy solution) based on Omnidirectional antennas. Moreover, the energy model is also rather simple, while we use a comprehensive energy model based on several characteristics such as frame size, modulation, transmission power and frame generation rates. However, the contribution in [8] related to switching components on/off based on dynamic traffic patterns is interesting and we also adopt this approach, i.e., after energy-efficient gateway placement, we can run the model online based on changing traffic patterns.

We first introduce an energy-efficient gateway placement scheme based on long-term traffic demands for mesh networks. Next, we introduce SINR-based physical interference model and propose a greedy scheme to efficiently find MISs. Next, we introduce the energy model and then formulate the optimization model as a MILP and propose an iterative algorithm for placing gateways. We also propose a heuristic based greedy algorithm to efficiently solve large problem instances. Finally, we provide numerical results on energy consumption of UDP traffic for the proposed scheme and other solutions in the area.

II. Energy-Aware Gateway Placement (EAGP)

We model the wireless mesh network as a directed graph $G=(\mathcal{N},E)$ where $i \in \mathcal{N}$ represents the set of vertices (mesh nodes), and $e_{ij} \in E$ is the set of edges (wireless links). Let $\psi(e_{ij})$ be the capacity of the directed wireless link e_{ij} such that $\psi(e_{ij}) \neq \psi(e_{ji})$. The *Forward Neighbors* of a node i is defined as the set: $\mathcal{FN}(i)=\{e_{ij}\in\mathcal{L}$: link e_{ij} is an outgoing link from $i\}$. The *Reverse Neighbors* of a node i is defined as the set: $\mathcal{RN}(i)=\{e_{ji}\in\mathcal{L}$: link e_{ji} is an incoming link to node $i\}$, and that $\mathbb{N}(i)=\mathcal{RN}(i)\cup\mathcal{FN}(i)$. Let $k\in\mathcal{K}$ be the set of flows in the network such that the tuple $(s_k\in S, t_k\in T, d_k\in D)$ represents the source, destination and traffic demand of flow k. The variable $f^k_{(e_{ij})}$ defines the amount of traffic for flow k that is placed on link e_{ij}. The mesh routers create the wireless mesh and also act as wireless APs to which users connect while a few routers in the network, called gateways, provide wired connection to the Internet. Let $\mathbb{G}=\{g_1,g_2,...|\mathbb{G}|\}$ be the set of gateways to be deployed in the network.

A. Interference Model

We adopt the *Physical Interference Model* [12] to model interference and assume the *Path-Loss* radio propagation model for signal reception, in which the signal received at node j from node i is represented by $\frac{P}{d^{\alpha}_{ij}}$, where P is the transmission
接受信号与距离成反比，与功率成正比

Usman Ashraf is with the Department of Communications and Networking, CCSIT, King Faisal University, Al-Ahsa, Saudi Arabia. (uashraf@kfu.edu.sa)

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power, d_{ij} is the Euclidean distance between nodes i and j and $\alpha > 2$ is the path-loss exponent for power-decay with distance. In this model, a transmission from node i to j is successful only if the *Signal-to-Interference-and-Noise-Ratio* (SINR) measured at receiving node j is above a threshold β:

$$SINR_j = \frac{P/d_{ij}^{\alpha}}{\sum_{n \in \mathcal{S} \setminus \{i\}} P/d_{nj}^{\alpha} + \eta} \geq \beta \tag{1}$$

where $\mathcal{S}$ is the set of links which are simultaneously active in a time-slot and η is the ambient noise. Without loss of generality, we assume uniform power and negligible ambient noise ($\eta \to 0$). The cumulative interference generated by conflicting links is modeled by a weighted conflict graph $G^{'} = (\mathcal{N}^{'}, E^{'})$ where each vertex $v'_{e_{ij}} \in \mathcal{N}^{'}$ actually represents link e_{ij} (links become vertices). A directed edge from $v'_{e_{uv}}$ to $v'_{e_{ij}}$ represents interference generated by transmitter u at receiver j provided the distance between u and j is less than r_u (interference range of transmitter u). The weight ($w_{v'_{e_{ij}}}^{v'_{e_{uv}}}$) of this directed edge is the maximum permissible noise from transmitter u that allows successful transmission on link e_{ij}.

We define a Maximal Independent Set (MIS) ($\mathcal{I}_x \in \mathbb{I}$) as the largest set of links which can be scheduled concurrently provided the end-points of link e_{ij} are not connected through any other node i.e. there is no node which is a neighbor of i and j i.e. $\{v'_{e_{ij}} \in \mathcal{S} : \mathbb{N}(i) \cap \mathbb{N}(j) = \phi\}$. For every link (called vertex here) $v'_{e_{ij}} \in \mathcal{I}_x$, the interference on this link due to other links cannot exceed 1, i.e. $\sum_{v'_{e_{mn}} \in \mathcal{I}_x} w_{v'_{e_{ij}}}^{v'_{e_{mn}}} \leq 1$. Set $\mathbb{I}$ comprises of all the maximal independent sets in the network. Let $\alpha_{\mathcal{I}_x}$ ($0 \leq \alpha_{\mathcal{I}_x} \leq 1$) be the fraction of time allotted to MIS $\mathcal{I}_x$, and $\mathbb{I}(e_{ij})$ be the set of MISs of which link e_{ij} is a part:

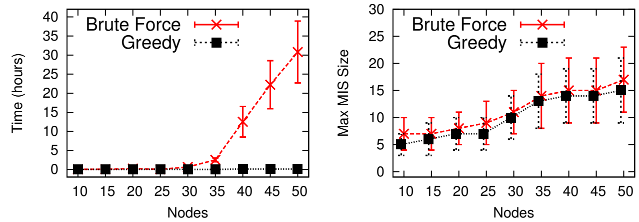
$$\sum_{\mathcal{I}_x \in \mathbb{I}} \alpha_{\mathcal{I}_x} \leq 1 \tag{2}$$

$$\sum_{k \in \mathcal{K}} f_{(e_{ij})}^{k} \leq \sum_{\mathcal{I}_x \in \mathbb{I}(e_{ij})} \alpha_{\mathcal{I}_x} \psi(e_{ij}) \tag{3}$$

Algorithm 1: Greedy Algorithm for MIS

Input: Weighted conflict graph $G^{'} = (\mathcal{N}^{'}, E^{'})$
Output: Set of maximal independent sets - $\mathcal{I}$

Procedure `Greedy()`
  $\mathbb{I}, \mathcal{I}_{curr} \leftarrow \{\}$;
  for *each vertex* $v'_{e_{ij}} \in E^{'}$ **do**
    $\Phi(v'_{e_{ij}}) = |\mathbb{N}(v'_{e_{ij}})| \cdot \sum_{v'_{e_{mn}} \in \mathbb{N}(v'_{e_{ij}})} w_{v'_{e_{ij}}}^{v'_{e_{mn}}} + w_{v'_{e_{mn}}}^{v'_{e_{ij}}}$;
  $\xi \leftarrow$ Sort vertices according to increasing Φ ;
  while $\xi \neq \{\}$ **do**
    $\xi_{curr} \leftarrow \xi$, $index \leftarrow 1$;
    while $\xi_{curr} \neq \{\}$ **do**
      Choose vertex $v'_{e_{ij}} \in \xi_{curr}$ at position $index$;
      $\xi_{curr} \leftarrow \{\xi_{curr} \setminus v'_{e_{ij}}\}$;
      Delete $v' \in \mathbb{N}(v'_{e_{ij}})$ which cause $SINR_j > 1$;
      $\mathcal{I}_{curr} \leftarrow \{\mathcal{I}_{curr} \cup v'_{e_{ij}}\}$;
      $index \leftarrow index + 1$;
    if $\mathcal{I}_{curr}$ *does not previously exist in* $\mathbb{I}$ **then**
      $\mathbb{I} \leftarrow \{\mathbb{I} \cup \mathcal{I}_{curr}\}$;
    Remove the first vertex from ξ;



(a) Computation time (b) Cardinality of the maximum IS

Fig. 1: Comparison of brute-force and greedy algorithms for MIS

These interference constraints are necessary and sufficient conditions for flow-scheduling, however, finding all the MISs is NP-Hard [12]. Therefore, we propose a greedy algorithm which provides an approximation i.e. finds a reasonable number of MIS from the weighted conflict-graph. We define the *Mutual Conflict Degree* $\Phi(v'_{e_{ij}})$ of a conflict-graph vertex as:

$$\Phi(v'_{e_{ij}}) = |\mathbb{N}(v'_{e_{ij}})| \cdot \sum_{v'_{e_{mn}} \in \mathbb{N}(v'_{e_{ij}})} w_{v'_{e_{ij}}}^{v'_{e_{mn}}} + w_{v'_{e_{mn}}}^{v'_{e_{ij}}} \tag{4}$$

We sort vertices based on mutual conflict degree and add the least conflicting link to MIS if the degree is less than 1. We delete the neighboring vertices (which cause SINR to exceed 1) from the graph and move to the next vertex. Figure 1 shows the time computation and cardinality of the largest MIS found using optimal and greedy algorithms for several topologies for 95% confidence. The greedy algorithm quickly finds MISs compared to exhaustive search and these MISs are then used to solve constraints (13) and (14) in the optimization model.

B. Energy Model

We assume a comprehensive energy model based on state-of-the-art work in [13], in which authors have experimentally validated that 802.11 nodes consume energy due to several factors. In addition to power consumed when the device is transmitting, receiving, idle, or sleeping, they account for energy consumption due to frame size, modulation, transmission power and frame generation rates. Further, authors show that substantial energy consumption (called *cross-factor*), occurs as each individual frame crosses the protocol stack (OS, driver, NIC). The total power consumption of a node i is defined as:

$$P(i) = P_{idle}^{(i)} + P_{tx}^{(i)} \tau_{tx}^{(i)} + P_{rx}^{(i)} \tau_{rx}^{(i)} + \gamma_{xg} \lambda_g^{(i)} + \gamma_{xr} \lambda_r^{(i)} \tag{5}$$

where $P_{idle}^{(i)}$, $P_{tx}^{(i)}$, $P_{rx}^{(i)}$ are the energies spent in idle, transmitting and receiving states and $\tau_{tx}^{(i)}$, $\tau_{rx}^{(i)}$ are the fractions of airtime spent in transmission and receiving respectively and γ_{xg} is the cross-factor energy associated with the processing of each individual frame, regardless of frame size or radio transmission parameters, $\lambda_g^{(i)}$ is the frame generation rate and $\lambda_r^{(i)}$ is the frame reception rate at node i. Of these, $\tau_{tx}^{(i)}$, $\tau_{rx}^{(i)}$, $\lambda_g^{(i)}$ and $\lambda_r^{(i)}$ are variables, while the rest are constants and depend on device and communication parameters. The transmission and reception air time fractions $\tau_{tx}^{(i)}$ and $\tau_{tx}^{(i)}$ can be calculated as $\tau_{tx}^{(i)} = \lambda_g^{(i)} T_L$ where T_L is a function of frame size, modulation and other overheads such as Physical Layer Convergence Protocol preamble and the MAC overhead [13]. The frame generation and reception rates can be calculated from the flow on links and the frame size. Moreover, we assume that idle radios are turned off to conserve energy.

Apart from the mesh nodes, the gateways have a special role in that they interface the mesh network with the wired Internet. Therefore, the energy consumption of the gateways is due to the wireless radio interfacing with the mesh network as well as the switch connecting it to the wired network. At gateway i, the energy consumption of switch $P_{sw}(i)$ [14] becomes:

$$P_{sw}(i) = P_{chassis} + n_{lcards} \cdot P_{lcards} + \sum_{k=1}^{R} n_{ports,r} \times P_r \quad (6)$$

where $P_{chassis}$ is the power consumed by switch hardware, n_{lcards} is the number of line cards and P_{lcards} is the energy consumption of an active network line card with no ports turned on and P_r corresponds to the power consumed by a port running at rate $r \in \{r_1, .., r_m\}$. Therefore, the total network power consumption including mesh nodes and gateways is:

$$P = \sum_{i \in \mathcal{N} \cup \mathbb{G}} P(i) + \sum_{j \in \mathbb{G}} P_{sw}(j) \quad (7)$$

C. Solution Approach

We adopt the approach of [15] in which we divide the area into a grid and assume that gateways can only be placed at the center-point of each grid-box. The set of valid positions is $\mathcal{P} = \{(x_1, y_1), ...(x_z, y_z)\}$. Let $\sigma_{ij} = \{0 : e_{ij} \notin E, 1 : e_{ij} \in E\}$ be the binary decision variable which controls the creation of new links in the topology due to addition of new gateways. We create a virtual sink ϑ which we assume is connected to all the gateways with links of infinite capacity and that all egress network traffic is directed towards this sink. So we can modify the tuple (s_k, t_k, d_k) to (s_k, ϑ, d_k). We now develop the Mixed-Integer Linear Programming (MILP) formulation for Energy-Aware Gateway Placement (EAGP):

$$\min \ P \quad (8)$$

subject to:

$$\sum_{e_{ij} \in FN(i)} f^k_{(e_{ij})} \sigma_{ij} - \sum_{e_{ji} \in RN(i)} f^k_{(e_{ji})} \sigma_{ji} = 0 \qquad \forall i \in \mathcal{N} - \{S, T, \vartheta\} \quad (9)$$

$$\sum_{e_{s_k i} \in FN(s_k)} f^k_{(e_{s_k i})} \sigma_{s_k i} - \sum_{e_{j s_k} \in RN(s_k)} f^k_{(e_{j s_k})} \sigma_{j s_k} - d_k = 0 \qquad \forall i,j \in \mathcal{N}, s_k \in S \quad (10)$$

$$\sum_{e_{i\vartheta} \in RN(\vartheta)} f^k_{(e_{i\vartheta})} \sigma_{i\vartheta} - d_k = 0 \qquad \forall i \in \mathcal{N}, k \in \mathcal{K} \quad (11)$$

$$\sum_{e_{\vartheta i} \in FN(\vartheta)} f^k_{(e_{\vartheta i})} = 0 \qquad \forall k \in \mathcal{K} \quad (12)$$

$$\sum_{\mathcal{I}_x \in \mathbb{I}} \alpha_{\mathcal{I}_x} \leq 1 \quad (13)$$

$$\sum_{k \in \mathcal{K}} f^k_{(e_{ij})} \leq \sum_{\mathcal{I}_x \in \mathbb{I}(e_{ij})} \alpha_{\mathcal{I}_x} \psi(e_{ij}) \qquad \forall e_{ij} \in E \quad (14)$$

$$\sigma_{ij} \in \{0,1\}, f^k_{e_{(ij)}}, \psi(e_{ij}) \geq 0 \qquad \forall e_{ij} \in E, k \in \mathcal{K}$$

The objective function minimizes the network-wide energy consumption while constraints (9), (10) and (11) are flow conservation constraints. Constraint (12) represents the fact that ϑ absorbs all the flows. Constraints (13) and (14) represent the physical interference constraints developed previously.

We use algorithm 2 for Energy-Aware Gateway Placement (EAGP). The algorithm runs as many times as the number of gateways to be deployed, and in each iteration, it selects the best position based on the optimal result from the model. The selected gateway, is made part of the topology and the algorithm proceeds. The algorithm is expensive since the MILP is solved for all possible positions ($|\mathcal{P}| \times |\mathbb{G}|$). We propose a greedy algorithm which greedily places gateways in the network and solves the optimization problem only once. Our greedy criteria is to minimize the average distance to the nearest gateway for all sources while considering the amount of flow generated by each source. The greedy algorithm is inspired from the well known farthest-first traversal approximation algorithm for the *k*-center problem (NP-Hard), with the difference that we use *hop*-distance, prioritize sources with more flow and heuristically spread out gateways.

Algorithm 2: Optimal Gateway Placement Algorithm

Input: Graph $G = (\mathcal{N}, E)$;
No. of gateways to be added $= |\mathbb{G}|$;
Set of possible GW positions $\mathcal{P} = \{(x_1, y_1), ...(x_m, y_m)\}$
Output: Optimal Deployment of Gateways
$count \leftarrow 0, \quad min \leftarrow 0, \quad pos \leftarrow \phi$;
Procedure `Optimal Placement()`
  while $count < |\mathbb{G}|$ **do**
    $min \leftarrow 0$;
    for *each position* $(x_i, y_i) \in \mathcal{P}$ **do**
      Add node at (x_i, y_i) and new links to topology;
      $objValue \leftarrow$ solve EAGP;
      if $objValue \leq min$ **then**
        min $\leftarrow objValue$;
        $pos \leftarrow (x_i, y_i)$;
      Remove node at (x_i, y_i) and links in topology;
    Finalize gateway at position pos;
    increment $count$;

D. Performance Evaluation

We use a custom network simulator developed in Java for performance evaluation. The wireless standard used is 802.11 and Omni-directional antenna is assumed at each mesh node. The optimization model constraints are generated using Java and then passed to the state-of-the-art LP-solver CPLEX. We use both constant bit-rate and variable bit-rate traffic based on UDP protocol. We call EGAP using optimal gateway placement algorithm as "*Exact*" and the greedy solution

Algorithm 3: Greedy Gateway Placement Algorithm

Input: Graph $G = (\mathcal{N}, E)$;
No. of gateways to be added $= |\mathbb{G}|$;
Set of possible GW positions $\mathcal{P} = \{(x_1, y_1), ...(x_z, y_z)\}$;
Set of source nodes $S = \{s_1, s_2, ...s_{|S|}\}$;
Output: Set of selected GW positions ($\mathcal{P}_{sel}$)
$\mathcal{P}_{sel} \leftarrow \{\phi\}$, $metric \leftarrow 0$;
$\forall p \in \mathcal{P}, s_k \in S$, calculate *hop*-distance $dist(p, s_k)$;
for *each gateway position* $p \in \mathcal{P}$ **do**
  for *each source node* $s_k \in S$ **do**
    $metric(p) \leftarrow metric(p) + \frac{d_k \cdot dist(p, s_k)}{\sum_{i \in \mathcal{K}} d_i}$;
while $|\mathcal{P}_{sel}| \neq |\mathbb{G}|$ **do**
  for *each gateway position* $p \in \mathcal{P}$ **do**
    $metric(p) \leftarrow \frac{metric(p)}{d(p, \mathcal{P}_{sel})}$;
  Select position p with smallest $metric(p)$ & add p to $\mathcal{P}_{sel}$;

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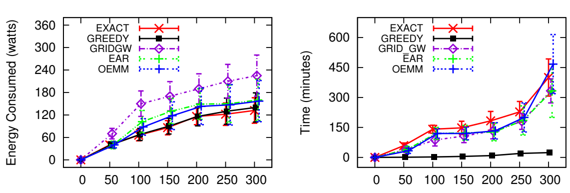
as "*Greedy*". We also implement three existing solutions: the grid-based gateway-deployment scheme [15] which optimizes gateway placement for throughput ("*GridGW*") and the energy-conservation based Energy-Aware-Routing (*EAR*) extension [3] which assumes energy depletion due to radios being "on". For fairness, we implement *EAR* using our physical-interference model. Further, we implement the energy-efficient part of [8], "*Optimal Energy Management Model*" *(OEMM)* using our physical interference model, omni-directional antennas and neglect constraints allowing users to choose AP.

1) Static Traffic Model: We first use a static traffic model which models long-term average throughput demands. We have ten UDP flows from random sources directed to a single gateway. Figure 2(a) and 2(b) show the energy and time consumption (95% confidence interval). *Exact* provides optimal energy conservation by optimally placing the gateways and using a comprehensive energy model. *OEMM* and *EAR* give similar performance due to similar optimization approach, but do not optimize gateway placement and use a basic energy model. *Greedy* performs quite close to *Exact* and also provides substantial time saving since it applies the optimization only once whereas others apply it at each iteration.

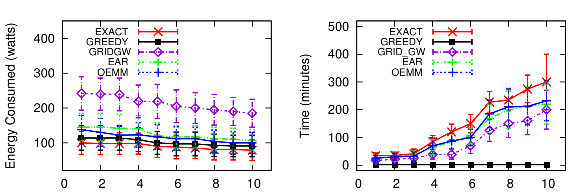
For the next experiment, we consider a 100 node topology with ten UDP flows and vary the number of gateways. Results in figure 3(a) and 3(b) show that, as more gateways are added, the availability of better routes results in energy reduction but an increase in time consumption due to additional constraints. The greedy scheme again offers the least time consumption, however, its optimality gap increases compared to the exact solution. *GridGW* performs poorly as it optimizes throughput and both *OEMM* and *EAR* neglect gateway placement and assume a basic energy consumption model.

2) Dynamic Traffic Model: Traffic variations affect [8] the performance of energy-efficient schemes and we now use variable traffic. We assume that gateways have been deployed at specific positions for all schemes, and we focus on the energy-efficient component of these solutions. We use a 100 node topology, ten UDP sources and 3 gateways, and divide the experiment duration into five separate slots. In each slot, we generate traffic randomly in the interval: 1-5 Mbps for



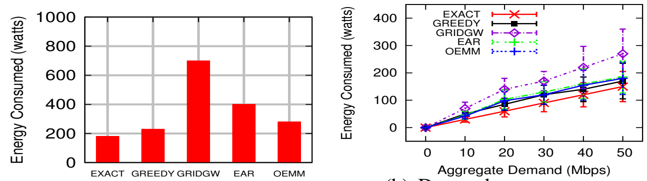
(a) Energy consumption (b) Computation time

Fig. 2: Energy and time consumption with topology size



(a) Energy consumption (b) Computation time

Fig. 3: Energy and time consumption with no. of gateways



(a) Variable traffic (b) Demand-energy curve

Fig. 4: Varying traffic and demands

each source. The final result, shown in figure 4(a) is the sum of energy values for all the intervals combined. *OEMM* performs significantly better than *EAR* compared to the static traffic case. However, both *EXACT* and *GREEDY* outperform *OEMM* since they assume a more comprehensive energy model. We also conduct an experiment to study the energy-optimality performance under different throughput demands. We use a 100 node topology, three gateways and ten UDP flows, and vary the aggregate demands from 10 Mbps to 50 Mbps. The results in figure 4(b) show that energy consumption increases almost linearly for all schemes since more wireless traffic translates into greater energy consumption in the network.

E. Conclusion

In this letter, we proposed an optimal gateway placement scheme for wireless mesh networks which minimizes the global network energy consumption. We also proposed greedy algorithms for efficiently finding the MISs for the physical interference model and for heuristics-based gateway placement. Numerical results show that the proposed solution outperform existing solutions in terms of energy and computation time.

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