PaMeLA: A Joint Channel Assignment and Routing Algorithm for Multi-Radio Multi-Channel Wireless Mesh Networks with Grid Topology

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Abstract— *The performance of multi-radio multi-channel Wireless Mesh Networks (WMNs) based on the IEEE 802.11 technology depends significantly on how the channels are assigned to the radios and how traffic is routed between the access points and the gateways. In this paper we propose an algorithmic approach to this problem, for which no conclusive solution has been put forward in the literature so far. The core of our scheme, called PaMeLA, consists of splitting the overall Joint Channel Assignment and Routing (JCAR) problem into a number of local optimization sub-problems, one for every node of the WMN, that are solved sequentially. Any sub-problem is formulated as an Integer Linear optimization Problem (ILP), whose optimal solution can be found using branch-and-cut in a reasonable amount of time. The final solution is obtained after a post-processing phase. In its current form, the algorithm is tailored to suit WMNs with a single gateway in a square-grid topology, which is of practical interest in many application scenarios. PaMeLA is compared through detailed packet-level simulation with several state-of-the-art JCAR algorithms and it is shown to attain better performance, in terms of the packet loss rate.*

I. INTRODUCTION

Wireless Mesh Networks (*WMNs*) consist of three types of wireless nodes [1]: clients, routers and gateways. The mesh clients are the end-user devices, typically mobile or nomadic. The mesh routers are fixed stations that form a multi-hop wireless backbone between the mesh clients and the mesh gateways: each client is connected to one mesh router to have its packets forwarded from/to a mesh gateway. Finally, the mesh gateways are mesh routers with Internet connectivity. In this work we focus on the backbone tier alone.

Even though the IEEE 802.11 technology does not provide native support for multi-hop forwarding and other WMN-related features, most WMNs are made of off-the-shelf IEEE 802.11 devices, because of their widespread availability and very low cost. WMN capabilities are then added in software [2]. Task group 's' has been created within the IEEE 802.11 working group to amend the standard and add the missing WMN functions, but the standardization process is not yet terminated [3]. One of the most important functions needed is routing. In fact, the existing routing protocols for wired networks, like the Open Shortest Path First (*OSPF*), are either inadequate and inefficient [4]. Therefore, routing protocols from the domain of ad-hoc wireless networks, like Ad-hoc On-demand Distance Vector (*AODV*) or Optimized Link State Routing (*OLSR*), are commonly re-used in WMNs.

Unlike mesh clients, which are most often equipped with a single radio device, the mesh routers typically have many radios, or Network Interface Cards (*NIC*s), to increase the network capacity [5]. In fact, by setting the radios on orthogonal non-interfering channels, multiple packets can be transmitted over-the-air simultaneously without colliding with one another. In a multi-channel environment, any two nodes can only communicate with one another if they are in the transmission range of one another *and* they have at least one radio set on a common frequency. For this reason, the processes of routing and channel assignment are very much inter-related. Moreover, both depend on the traffic load distribution. For instance, more frequency diversity can be allocated to those areas of the WMN which are expected to have a higher load, to cope with the limited availability of channels.

In the literature, the problem of channel assignment in WMNs has been considered mapped to the know problem of finding the minimum number of colors to be assigned to nodes in a graph [6], such that adjacent nodes never have the same color. While these works are important from a theoretical point of view, they remain somewhat limited for practical implementation, because network-specific constraints and objective functions, e.g. traffic load or cumulative interference model, cannot be captured in a straightforward manner. The problem of Joint Channel Assignment and Routing (*JCAR*) has been formulated also as an Integer Linear Problem (*ILP*), e.g. [7]. Since the problem is $\mathcal{NP}$-hard, no approach exists to find the optimal algorithm in a reasonable amount of time, for non-trivial WMNs. Therefore, some heuristics have been proposed, e.g. [8, 9]. Furthermore, to model interference, *protocol model* assumptions are often made. This simplistic approach considers as negligible the effect of cumulative interference from multiple nodes transmitting at the same time [10]. In this paper, we tackle the JCAR problem, with cumulative interference, by proposing a novel approach, called Partitioned Mesh network traffic and interference aware channeL Assignment (*PaMeLA*). The core of our method consists of solving a sequence of sub-

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problems, one for every node, in a given order. Each sub-problem is much simpler than the global JCAR problem, because only the local constraints on interference are tested. The solution obtained is refined via a post-processing procedure. In this work we focused on a specific scenario, which is of particular interest for WMNs [11], where the nodes are placed in a square-grid topology, and the gateway is located in a corner. The order in which sub-problems are solved and the post-processing are optimized for this scenario. Extension of PaMeLA to the general case is an ongoing research activity.

The remainder of the paper is organized as follows. In Section II we define the system model and assumptions, and describe PaMeLA, while the state-of-the-art is summarized in Section III. The performance evaluation is reported in Section IV, and Section V concludes the paper.

II. PAMELA

In this section we describe the system model and assumptions on which PaMeLA is based, along with the notation used.

A. System model and assumptions

In the following we distinguish between logical and physical links. A *physical link* exists between any two nodes if they are in the transmission range of one another. Two nodes that share a physical link are called *one-hop neighbors* (or *neighbors*, for short), while two nodes that have a common neighbor, but are not neighbors themselves are said *two-hop neighbors*. A topology consisting of physical links is called *physical topology*. On the other hand, a *logical link* between any two nodes means that (i) a physical link exists between them, (ii) they have at least one NIC set to the same channel, and (iii) there is at least one traffic flow traversing them. The definition of *logical topology* follows. Hereafter, the terms router and node are used interchangeably.

We assume that the process to assign channels and determine the routing paths, using PaMeLA, is run periodically in the WMN by a centralized entity, which is also responsible for disseminating the updated channel assignment and routing to all nodes. Such a process can be carried out as part of the duties of existing routing protocols for WMNs. The procedure is provided with input on the configuration parameters and the current status of the WMN, which can be retrieved by means of a network management protocol running in the WMN. The network functions to collect data from nodes to the centralized entity and to enforce the channel assignment and routing that it produces are outside the scope of this work, which focuses only on the algorithm that it runs.

The centralized entity running PaMeLA requires the following configuration parameters. First, it needs the physical topology, which can be represented as a graph $G(N, E)$, where N is the set of nodes and E is the set of unidirectional physical links. We indicate with $|N|$ and $|E|$ the cardinality of sets N and E, respectively. In the following we indicate with h^{sd} the minimum hop path from node s to node d in $G(N, E)$. Second, the configuration parameters include the number of NICs per node. To simplify the notation, without loss of generality, we assume that every node is equipped with the same number of NICs, equal to K. Then, the number of available channels is Chl. In the IEEE 802.11 we have 3 and 12 orthogonal frequency channels for the standard 'b'/'g' and 'a' [12], respectively. The limited number of channels implies that some logical links must be assigned to the same channel, i.e. these links cannot be active simultaneously, except for very small networks. Finally, PaMeLA requires knowledge on the received power at node q when node p is transmitting, indicates as Φ_{pq}. The received power is proportional to the transmitted power and inversely proportional to the Euclidean distance between nodes. The concepts of received power and interference are closely related, we will define the interference model in Section II.B.1).

The current status of the WMN includes the channel rate and the traffic load. The channel rate Ψ^{k}_{pq} represents the nominal data rate of the link e_{pq} on channel k. For instance, with IEEE 802.11a technology the channel rate ranges from 6 Mb/s to 54 Mb/s. With regard to both the received powers and the channel rates, it is worth noting that the nodes in a WMN are static, hence channel conditions are rather stable [2]. Estimating the physical layer status such as that required by PaMeLA has been investigated recently in the literature, e.g. [13], and it is not considered further in this work. Finally, the traffic load from any source node s to any destination node d in the WMN, indicated as γ^{sd}, is needed. In practice, such information is either available as *a priori* knowledge, based on historical data, or it can be estimated while the WMN is operated.

We assume that the nodes in the WMN are located so as to obtain a square-grid as physical topology graph. This kind of networks are widely used in both theoretical and experimental studies on WMNs [9, 14, 15, 16], and they have been shown via numerical analysis in [11] to have some beneficial properties, with respect to, e.g., networks where nodes are uniformly distributed. Therefore, they are of practical interest in those application scenarios where the WMN is deployed from scratch by a network operator, e.g. municipal wireless. Furthermore, we consider the case of a single gateway to the Internet. In fact, if there are $\theta > 1$ gateways, then the overall problem can be divided into θ sub-problems that are solved individually using PaMeLA. The nodes can be assigned to each sub-problem based on a combination of factors, including the distance from the gateway and the traffic load. Finally, for simplicity of illustration, the gateway is assumed to be located in a corner of the WMN, which is visualized in the figures as the top-left corner. The extension to the case when the gateway is located in an arbitrary position within the square-grid is straightforward. Several cases were thoroughly analyzed but their related assessments are not reported here due to limited page budget.

The notation used throughout this work is summarized in Table I.

B. Algorithm description

The system model and assumptions reported in the previous section are typical in most studies on the JCAR problem in the literature, which are reviewed in Section III and can be broadly classified into two categories: (i) those modeling the JCAR

TABLE I. NOTATION.

Symbol	Value
N	Set of nodes
E	Set of edges
Chl	Number of channels
K	Number of radios for each node
Λ	Maximum link utilization
Γ	Maximum routing length
Φ_{pq}	Received power at q when p is transmitting
Ψ^{k}_{pq}	Channel rate of link e_{pq} for channel k
γ^{sd}	Traffic load from node s to node d
β	Interference threshold
h^{sd}	Minimum hop path between node s and node d
C	Set of network crews
R	Set of ranking functions
U	Set of criteria to assign channels to unused NICs
$\mathcal{P}$	Set of JCAR problems. $\mathcal{P}_{c,r} \in \mathcal{P}$ is a specific instance with network crew c and ranking function r
$\sigma_{c,r,u}$	Solution to problem $\mathcal{P}_{c,r}$, using criterion u in the second phase

problem as a mathematical optimization problem, which is proved to be $\mathcal{NP}$-hard, then solved by relaxing the constraints or using a heuristic sub-optimal algorithm [7, 18]; (ii) those proposing empirical algorithms, whose effectiveness is typically verified through simulation [8, 9, 14, 17, 19].

In this work we propose a different approach, which consists of two phases and can be outlined as follows. In the first phase we use an inner core procedure, which finds the optimal solution of a sequence of sub-problems. Each sub-problem is formulated as an ILP, whose output defines the channel assignment and routing local to a single node. One sub-problem per node is solved. Due to the limited number of constraints, these sub-problems can be solved optimally in a reasonable amount of time with standard solvers, e.g. using branch-and-cut techniques [24]. Multiple instances of the inner core procedure are run, by ordering the execution of sub-problems based on different ranking functions and enforcing different routing constraints via so-called *network crews*. In the second phase of PaMeLA, for each instance we apply a post-processing phase, which ensures that the resulting logical topology is connected and that there are no unused NICs. The best solution is selected among all the instances, according to a max-min fairness criterion combined to a load-aware interference objective. The two phases are described separately below.

1) JCAR phase

Before providing a formal description of the first phase of PaMeLA, we need to introduce network crews and ranking functions concepts.

A network crew $c \in C$ is a way to define a number of sub-sets of N, indicated as N_c^i. For every sub-set a single node is selected as sub-gateway. The sub-gateway must be a one-hop neighbor of the gateway, which does not belong to any sub-set. A given network crew c adds the following constraint to JCAR problem: all the nodes in a sub-set can only reach the gateway through the respective sub-gateway. If there are nodes, other

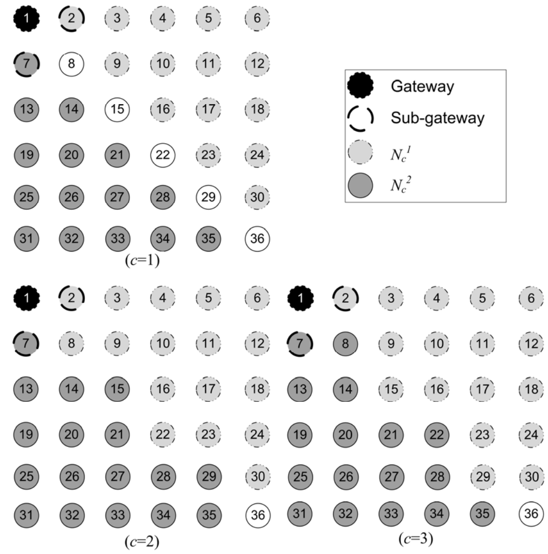

Figure 1. Network crews for a 6×6 grid.

than the gateway, that do not belong to any sub-set, traffic flows originating from them can follow an arbitrary path. The idea behind the use of network crews is to balance traffic among the gateway's links, which are likely to become congested during the network operation. We found that using any of the three network crews illustrated in the example in Fig. 1 give good results in all the networks and traffic configurations tested.

On the other hand, a ranking function $r \in R$ is a criterion to sort the nodes in N. This function will be used to determine the order of solution of the sub-problems, as described below. For the scenario investigated in this paper, we tested the two ranking functions illustrated in the example in Fig. 2. The rationale driving this decision is that a node closer to the gateway is more critical than a peripheral one, since it relays more traffic. Therefore, such a node should be considered at an early stage of channel assignment and path selection.

For any network crew c in the set C, and for any ranking function r in the set R, we define $\mathcal{P}$ as the set of channel assignment and routing problems where $\mathcal{P}_{c,r}$ is a specific instance of $\mathcal{P}$. Let's further denote with $\mathcal{P}_{c,r}$ the solution of the JCAR problem $\mathcal{P}_{c,r}$. Thus, the maximum number of instances output at the end of the first phase, and passed to the post-processing phase, is $|C| \times |R|$, but there can be less, in case no solution is found for one or more instances.

Every instance $\mathcal{P}_{c,r}$ is solved via the following sequential iterative algorithm. Nodes are visited one by one in the order defined by r, hence the total number of iterations is $|N|$. The node being visited is called *tagged node*, indicated as $t \in N$. An ILP instance, indicated as $\mathcal{P}^{t}_{c,r}$, is formulated including the routing constraints from the network crew c, and all the constraints on routing, capacity, and interference that affect the one-hop neighborhood of the tagged node, plus all the constraints due to any previously assigned channel and selected path for nodes that have been already visited before the current

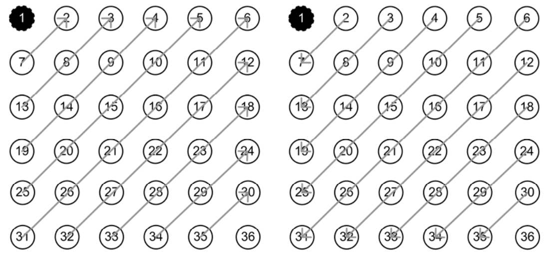

Figure 2. Ranking functions for a 6×6 grid

one. Therefore, the set of constraints of problem $\mathcal{P}^i_{c,r}$ is a superset of the constraints of any other problem $\mathcal{P}^j_{c,r}$, with $j = 0, \ldots, i-1$. The solution $\sigma_{c,r}$ is eventually obtained by combining together all the channel assignment and routing choices in all the iterations. The workflow is reported in the pseudo-code in Fig. 3.

We conclude by formulating in Fig. 4 the problem $\mathcal{P}^t_{c,r}$ as an integer linear optimization problem, using mathematical notations, where E_t is defined as the set of unidirectional physical links of t:

$$E_t = \left\{ E_{t*} \cup \left[\left(\bigcup_{p \in N; e_{pt} \in E} E_p \right) \cap \left(\bigcup_{ord(p) \prec ord(t)} E_p \right) \right] \right\}, \qquad (1)$$

where $E_{t*} = \{(p, q) \in E: p == t \vee q == t\}$. The ILP has many working variables, which are described in Table II.

As proposed in [7], the ILP also uses as input two tunable parameters, i.e. $\Lambda \leq 1$ and $\Gamma \geq 1$, which represent an upper bound on the expected link utilization and on the routing length, respectively. More specifically, in practical networks, the channel rate cannot be used entirely due to the Medium Access Control (*MAC*) and physical layer overhead, including headers, collisions, inter-frame spaces, preambles, antenna switching gaps. With Λ we force PaMeLA to utilize only a fraction of the nominal capacity, by leaving room for any such overhead. On the other hand, Γ is used to force the inclusion of those routing paths that are longer, in terms of the number of hops, than the shortest ones. Say, if $\Gamma = 1.5$ and there is a path in the physical topology graph from node *s* to node *d* of length 4, then all the paths shorter than or equal to 6 hops are considered as eligible. As a special case, with $\Gamma = 1$, only paths of minimum length are allowed. Finally, we also consider another tunable parameter, indicated as β, to represent the resilience to interference. Let us consider a node *p.* Depending on path-loss and other effects, nodes outside its one-hop neighborhood can or cannot interfere with transmissions from *p*. This is not know *a priori*, but still an assumption has to be made in the ILP formulation. With β we decide how strict PaMeLA is with respect to this assumption, by decreasing β we increase the spatial re-use in the network, but also the number of concurrent transmissions, hence the interference. In any case, the absolute value of β depends on the received power provided as input.

We now discuss the constraints in Fig. 4: (4) and (5) denote that the links must be bidirectional and that the number of NICs

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let P0 be a JCAR problem with basic constraints
find the set R of possible rankings
find the set C of possible network crews
for each c ∈ C do        // |C| = 3 in square-grid
  Pc = P0 + constraints due to c
  for each r ∈ R do       // |R| = 2 in square-grid
      for each node t ∈ N sorted as r do
          // t is the tagged node
          produce P^t_{c,r} by adding constraints
          from the previous solution obtained
          σ^t_{c,r} = solve ( P^t_{c,r} )
          if σ^t_{c,r} = ∅ then break
      if ∃ σ^t_{c,r} such that σ^t_{c,r} = ∅ then
          σ_{c,r} = ∅
      else
          σ_{c,r} = combine ( σ^t_{c,r} , t = 1, …, |N|)
```

Figure 3. First phase: pseudo-code.

per node is limited, respectively; (6) and (7) are the logical topology constraint [7]; (8) states that the tagged node can only communicate with a one-hop neighbor via a single NIC. This limit is relaxed in the post-processing phase; (9) limits the effective capacity, defined in Table II, to the channel rate; (10) limits the utilization, defined as the fraction of time that is spent for transmission, of any logical link [7]; (11) defines the aggregate traffic, as in Table II; (12) limits the aggregated traffic based on Λ; (13) and (14) define the variable $y^k_{g,pq}$ (see Table II); (15) limits the spatial re-use, see the definition of β above; (16) and (18) are routing constraints well-know in the literature [7, 20]; (17) forces bi-directional traffic to follow the same path. This constraint has been added because empirical evidence suggests that this leads to using less channels per node, yielding better solutions. This constraint is relaxed in the post-processing phase; (19) limits the path length, based on Λ.

The objective function, expressed in (3), has been first defined in [7], though in a slightly different formulation. This represents an attempt to reach localized per-node max-min fairness, since it maximizes the minimum difference between the channel rate and the traffic load across all channels and all links around the tagged node. For a given solution $\sigma_{c,r}$, the overall objective function $\delta_{\min}$ is derived as the maximum over all $\delta^t_{\min}$, for each node $t \in N$.

2) Post-processing phase

The goal of this second phase, called post-processing, is to fix the following two issues in the solutions produced in the first phase: (i) the network can be disconnected; and (ii) there can be some NICs that are not set on any channel. Fixing these issues would not be needed if the solution were found by solving a global optimization problem, like that proposed in [7], which takes into accounts all the constraints at the same time. Post-processing consists of two subsequent steps, which are described below and illustrated by means of the pseudo-code in Fig. 5. In this phase we use the following metric to decide which is the best solution:

$$D_{tot} = \sum_{k=1}^{Chl} \left[\sum_{\substack{p \in N \\ e_{pg} \in E}} \left(l^k_{pg} \cdot 2^{MAXhop - hop_{p,\Theta}} + \sum_{\substack{q \in I_p \\ e_{qg} \in E}} l^k_{qg} \cdot 2^{MAXhop - hop_{q,\Theta}} \right) \right], \qquad (20)$$

$$\textbf{find} \ \max \quad \delta^t_{\min} \tag{2}$$

$$\delta^t_{\min} = \min_{p,q\in N; e_{pq}\in E; k\in\{1,\ldots,Chl\}; x^k_{pq}=1} \left(\Lambda\cdot\varphi^k_{pq} - l^k_{pq}\right), \quad \forall p,q\in N; e_{pq}\in E_t; \forall k=1,\ldots,Chl. \tag{3}$$

Channel allocation constraints

$$x^k_{pq} = x^k_{qp}, \quad \forall p,q\in N; \forall e_{pq}\in E_t; \forall k=1,\ldots,Chl. \tag{4}$$

$$\sum\nolimits_{k=1}^{Chl} y^k_p \le K, \quad \forall p\in N: ord(p)\ge ord(t). \tag{5}$$

$$y^k_p \le \sum\nolimits_{e_{pq}\in E} x^k_{pq}, \quad \forall p\in N: ord(p)\ge ord(t); \forall k=1,\ldots,Chl. \tag{6}$$

$$x^k_{pq} \le y^k_p, \quad \forall e_{pq}\in E: ord(p)\ge ord(t); \forall k=1,\ldots,Chl. \tag{7}$$

$$\sum\nolimits_{k=1}^{Chl} x^k_{pq} \le 1, \quad \forall e_{pq}\in E_t. \tag{8}$$

Capacity constraints

$$\varphi^k_{pq} \le x^k_{pq}\cdot\Psi^k_{pq}, \quad \forall p,q\in N; e_{pq}\in E_t; \forall k=1,\ldots,Chl. \tag{9}$$

$$\sum\nolimits_{e_{pq}\in E_t} \frac{\varphi^k_{pq}}{\Psi^k_{pq}} + \sum\nolimits_{e_{qp}\in E_t} \frac{\varphi^k_{qp}}{\Psi^k_{qp}} \le 1, \quad \forall p\in N; \forall k=1,\ldots,Chl. \tag{10}$$

Traffic constraints

$$l^k_{pq} = \sum\nolimits_{s,d\in N} rt^{sd}_{pq,k}\cdot\gamma^{sd}, \quad \forall p,q\in N; e_{pq}\in E_t; \forall k=1,\ldots,Chl. \tag{11}$$

$$l^k_{pq} \le \Lambda\cdot\varphi^k_{pq}, \quad \forall p,q\in N; e_{pq}\in E_t; \forall k=1,\ldots,Chl. \tag{12}$$

Interference constraints

$$y^k_{g,pq} \le \sum\nolimits_{e_{gh}\in E: h\ne p, h\ne q} x^k_{gh}, \quad \forall g\in N: e_{gp}\in E \wedge g\ne q; \forall e_{pq}\in E: p=t \vee q=t; \forall k=1,\ldots,Chl. \tag{13}$$

$$x^k_{gh} \le y^k_{g,pq}, \quad \forall e_{gh}\in E: h\setminus\{g,p,q\}; \forall e_{pq}\in E_t: e_{gq}\in E \wedge g\ne p, p==t \vee q==t; \forall k=1,\ldots,Chl. \tag{14}$$

$$\Phi_{pq} \ge \beta\cdot\sum\nolimits_{e_{gq}\in E: g\ne p} \Phi_{gq}\cdot\left(y^k_{g,pq} + x^k_{pq} - 1\right), \quad \forall p,q\in N; e_{pq}\in E_t: p==t \vee q==t; \ \forall k=1,\ldots,Chl. \tag{15}$$

Routing constraints

$$\sum\nolimits_{k=1}^{Chl} rt^{sd}_{pq,k} \le 1, \quad \forall s,d,p,q\in N; e_{pq}\in E_t: p==t \vee q==t. \tag{16}$$

$$rt^{sd}_{pq,k} = rt^{sd}_{qp,k}, \quad \forall s,d\in N; e_{pq}\in E; \forall k=1,\ldots,Chl. \tag{17}$$

$$\sum\nolimits_{e_{pq}\in E}\sum\nolimits_{k=1}^{Chl} rt^{sd}_{pq,k}\cdot\gamma^{sd} - \sum\nolimits_{e_{qp}\in E}\sum\nolimits_{k=1}^{Chl} rt^{sd}_{qp,k}\cdot\gamma^{sd} = \begin{cases} \gamma^{sd}, & if\ s=p \\ -\gamma^{sd}, & if\ d=p \\ 0, & otherwise. \end{cases}, \quad \forall p\in N: ord(p)\ge ord(t). \tag{18}$$

$$\sum\nolimits_{e_{pq}\in E}\sum\nolimits_{k=1}^{Chl} rt^{sd}_{pq,k} \le \Gamma\cdot h^{sd}, \quad \forall s,d\in N. \tag{19}$$

Figure 4. ILP formulation of the JCAR problem.

where I_p represents the set of nodes whose transmissions would interfere with those from node *p* if occurring in overlapping time intervals, *MAXhop* denotes the minimum length, in number of hops, between the gateway and its furthest node in the logical topology and $hop_{p,\theta}$ is the path length, in number of hops, between the node *p* and the gateway in the currently selected routing. D_{tot} represents the total interference weighted on the traffic load and the distance from the gateway.

The first step is to force the network to be connected by adding more logical links. In general a network is connected if any node can reach any other node through at least one path of arbitrary length. This definition is used to build the procedure detailed in the first step of Fig. 5, which adds logical links to any solution $\sigma_{c,r}$ until the logical topology becomes connected. This is achieved by creating those logical links that incur the least interference, according to D_{tot}. The second step then consists in adding logical links, in case there are some NICs that have not been assigned channels. Provided that a node *p* has an unused NIC, in order to improve the quality of the solution, we define *U* as the set of the following three criteria.

1. if there is a neighbor with an unused NIC too, set them to a common channel *k*;
2. otherwise, if *p* is not a bottleneck node, i.e. if $\delta^p_{\min}$ is greater than the overall $\delta_{\min}$, set the unused NIC to a common channel *k* with a neighbor;
3. re-use a channel *k* to add a logical link anyway.

Any of the three criteria above is less restrictive than the previous ones. In all cases, the channel *k* is selected so as to minimize D_{tot}.

Thus, for every solution $\sigma_{c,r}$ obtained from the first step, the output of the second step is a set of three solutions $\sigma_{c,r,1}$, $\sigma_{c,r,2}$, and $\sigma_{c,r,3}$. The exact procedure is reported in Fig. 5.

// step 1: fix disconnected nodes
for each $c \in C, r \in R$ **do**
  for each node $t \in N$ sorted as r **do**
    the current solution is $\sigma_{c,r}$
    if t is the gateway **then continue**
    if t can reach the gateway **then continue**
    find the pair $\langle q, k\rangle$ such that: activating channel k on the link e_{tq} creates a path from node t to the gateway, with the min. D_{tot}
    if no $\langle q, k\rangle$ **then continue**
    in $\sigma_{c,r}$ set $x_{tq}^k = x_{qt}^k$ and $y_t^k = 1$
// step 2: assign channels to unused NICs
for each $c \in C, r \in R$ **do**
  for each criterion $u \in U$ **do**
    $\sigma_{c,r,u} = \sigma_{c,r}$
    for each node $t \in N$ sorted as r **do**
      while $\sum_{k=1}^{Chl} y_t^k < K$ **do**
        // criterion 1
        if $u = 1$ **then** find the pair $\langle q, k\rangle$ such that: activating channel k on the link e_{tq} yields $\sum_{k=1}^{Chl} y_q^k < K \wedge y_q^k = 0$ and produces the minimum D_{tot}
        // criterion 2
        if $u = 2$ **and** node t does not have the minimum $\delta_{\min}$ in $\sigma_{c,r,2}$ **then** find the pair $\langle q, k\rangle$ such that: activating channel k on link e_{tq} yields $\sum_{k=1}^{Chl} y_q^k = K$ and produces the minimum D_{tot}
        // criterion 3
        if $u = 3$ **then** find the pair $\langle q, k\rangle$ such that: activating channel k on the link e_{tq} yields produces the minimum D_{tot}
        // create a new logical link
        if no $\langle q, k\rangle$ **then continue**
        in $\sigma_{c,r,u}$ set $x_{tq}^k = x_{qt}^k$ and $y_t^k = 1$

Figure 5. Second phase: pseudo-code.

After all the possible solutions are found, whose number is smaller than or equal to $|C| \times |R| \times |U|$, the final solution is:

$$\bar{\sigma} = \underset{\substack{\sigma_{c,r,u} \\ c\in C, r\in R, u\in U}}{\arg\max} \frac{\delta_{\min}(\sigma_{c,r,u})}{D_{tot}(\sigma_{c,r,u})}, \quad (21)$$

i.e. the one that provides the best compromise between the max-min fairness and the load-aware interference objectives.

III. RELATED WORK

As already introduced, joint channel assignment and routing is perceived as a key problem in the context of WMNs, as demonstrated by the amount of works that appeared in the literature recently. In the following we review the previous works that are more relevant to this study.

In [7] the authors propose an ILP formulation to address the overall JCAR problem. The problem is proved to be $\mathcal{NP}$-hard, and a heuristic algorithm based on choosing randomly the initial solution, then refining it within a limited configurable number of steps, is proposed to trade the solution's accuracy for a (much) faster execution time. The constraints and objective function of the problem in [7] are adapted to the local per-node problem that we propose in this work as part of PaMeLA.

Due to the inherent complexity of the JCAR problem, many heuristic algorithms have been proposed, a fraction of which aim at minimizing interference. In [8] the authors proposed the Connected Low Interference Channel Assignment (*CLICA*), which is based on the use of a conflict graph. In [19] the authors proposed a JCAR algorithm suitable to be performed by a central server that periodically collects dynamically-changing channel interference information. However, the problem addressed in [8] and [19] differ from that investigated in this work since the former does not consider the traffic load on links, which is instead taken into account by PaMeLA.

TABLE II. JCAR PROBLEM VARIABLES.

Symbol	Name	Definition
x_{pq}^k	Link channel allocation	It is 1 if node p communicates with node q over the channel k, 0 otherwise. This variable expresses the logical topology.
y_p^k	Node channel allocation	It is 1 if $\exists\, p \in N$ and $e_{pq} \in E$ such that $x_{pq}^k = 1$, 0 otherwise.
$y_{g,pq}^k$	Interference	It is 1 if $\exists\, g, p \in N$ and $e_{pq} \in E$ such that $y_g^k = x_{pq}^k = 1$ over the same channel k, 0 otherwise.
φ_{pq}^k	Effective capacity of a logical link	It is proportional to the traffic that crosses the link $e_{pq} \in E$ and to the number of NICs over channel k.
$rt_{pq,k}^{sd}$	Binary routing	It is 1 if the traffic from source node s to destination node d is being routed via link e_{pq} over channel k, 0 otherwise.
l_{pq}^k	Aggregate traffic	Sum of the traffic on link e_{pq} over channel k.

The following solutions, instead, pursue the same objective as PaMeLA, hence they have been evaluated for comparison purposes in the performance analysis in Section IV. First, Raniwala et al. [9] proposed a centralized heuristic Load-Aware joint Channel Assignment and routing algorithm, called *LACA*. The proposed algorithm can be used in combination with any routing mechanism. The same authors also proposed *Hyacinth* [14], which is optimized for scenarios where the physical topology graph is a tree. Finally, in [17] the authors proposed the Flow-based Channel and Rate Assignment (*FCRA*) algorithm, which can be compared to PaMeLA by disabling the rate adaptation function. The heuristic algorithm proposed in [7] has not been compared, because the accuracy of the solutions founded depends substantially on the maximum number of steps run.

IV. PERFORMANCE EVALUATION

In this section we report a performance analysis of PaMeLA. First, in Section IV.A, we report the execution times of PaMeLA in several scenarios, to demonstrate that it can be run at the time scale of provisioning with non-specialized hardware. The rest of the analysis is carried out via detailed packet-level simulation, whose settings are described in Section IV.B. The results are discussed in Section IV.C.

A. Execution time analysis

PaMeLA has been implemented using the ILOG tools AMPL [1] and CPLEX [2] for describing and solving the ILP instances in the JCAR phase. Input preparation and post-

[1] URL: http://www.ampl.com/, version 11.21.
[2] URL: http://www.ilog.com/products/cplex/, version 11.21.

TABLE III. PHYSICAL LAYER PARAMETER VALUES.

	Minimum SINR for each PHY rate							
PHY rate (Mb/s)	6	9	12	18	24	36	48	54
SINR (dB)	9	10	11	13	17	20	25	27
Φ_T	17 dBm							
Band	5.15 GHz							
$\mathcal{H}$	-95 dBm							

processing has been implemented in C++. The results presented have been obtained with a dedicated Linux 2.6 workstation equipped with an Intel Core 2 CPU at 2.13 GHz and 2 GB of main memory. The C++ code has been compiled with the GNU gcc compiler version 3.4.6, with architecture-specific optimizations.

Figure 6 shows the execution time of PaMeLA against the grid size, with three different combinations of the number of available channels and the number of NICs per node. As can be seen, even with rather large WMNs, i.e. with more than 36 nodes, the execution time is relatively small. For comparison, solving the global JCAR problem with the same hardware and software used for PaMeLA becomes impractical, i.e. execution time in the order of many days, starting from 4×4 WMNs.

PaMeLa is easily scalable because the maximum complexity is given by the time needed to solve a single neighborhood.

B. Simulation environment

The simulation study has been carried out with ns-2[3], which has been modified to enable MRMC and to include a SINR-based physical interference model. Specifically, the SINR of the transmission from node p to node q, which takes place between time instants τ_1 and τ_2, is [22]:

$$SINR(p,q,\tau_1,\tau_2) = \frac{\Phi_{pq}}{\sum_{g \in \mathcal{T}(\tau_1,\tau_2)} \Phi_{gq} + \mathcal{H}}, \qquad (22a)$$

where Φ_{pq} is the received power at node q when node p is transmitting, $\mathcal{T}(\tau_1, \tau_2)$ is the set of nodes transmitting in the time interval $[\tau_1, \tau_2]$, and $\mathcal{H}$ is the background noise power. The received power, in turn, depends on the Euclidean distance $d(p, q)$, in meters, between node p and node q, the transmitted power Φ_T which is assumed to be the same for all nodes, the path loss exponent κ and the signal wavelength λ, in meters:

$$\Phi_{pq} = \frac{\Phi_T \left(\lambda/4\pi\right)^2}{d\left(p,q\right)^{\kappa}} \qquad (22b)$$

The MAC frame is assumed to be correctly received if the SINR is greater than or equal to the minimum value required by the IEEE 802.11 standard. The parameters used in the simulations, which refer to the IEEE 802.11a OFDM-based physical layer, are reported in Table III. Using the physical interference model, we can obtain a realistic measurement of the interferences resulting from channel assignment and routing decisions. The maximum number of retransmissions at the MAC layer was set to 7, which is the default in most devices. If this limit is exceeded, the packet is dropped. Another reason why a packet can be dropped is when it overflows a node's MAC buffer size, which was set equal to 100 packets. All experiments are conducted with RTS/CTS mechanism disabled.

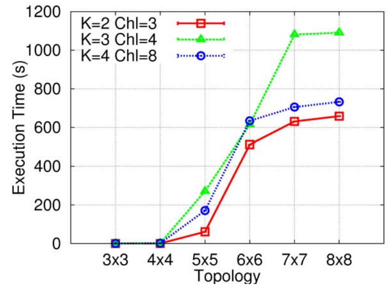

Figure 6. Execution time of PaMeLA against the grid size.

The nodes are arranged in a 6×6 square grid topology, where the distance between any two consecutive nodes has been varied from 50 m to 180 m. Due to limited page budget, only the results with 140 m are reported, where the channel rate of all links was 6 Mb/s. Depending on the scenario, every node in the WMN is equipped with a number of NICs (K) between 2 and 4, while the number of available channels (*Chl*) ranges from 3 to 12. As far as traffic is concerned, every node (except the gateway) is assumed to have exactly one Constant Bit-Rate (CBR) traffic flow towards the gateway, each flow is bidirectional. The packet size was kept constant to 1024 bytes. The following transmission rates have been considered: 26 Kb/s, 52 Kb/s or 104 Kb/s.

The duration of each simulation was 500 s, which has been verified to be enough for the simulated system to reach a steady-state. Samples were not collected during the first 100 s to remove the initialization bias. Several independent replications for each scenario have been run, according to the method of independent replications [23]. Mean values were then estimated along with 95% confidence intervals, which are not reported in figures whenever negligible.

As already mentioned, PaMeLA is compared to the following state-of-the-art JCAR solutions, with minor modifications: Hyacinth [14], FCRA [17], and LACA [9]. Additionally, random channel assignment was considered as a reference. PaMeLA has been configured with $\Lambda = 0.8$, $\Gamma = 1$, $\beta = 3.5$.

To assess the performance, the following performance indices have been used. First, the collision probability is defined as the probability that a packet experienced a collision along the path from source to destination node. Then, the normalized throughput for a given JCAR scheme is defined as the throughput, i.e. the number of bits received by the destination nodes in the unit of time, obtained with the JCAR schemes divided by the random channel assignment scheme throughput. Finally, the packet loss is the ratio between the number of packets sent by the source node and the number of packets correctly received by the destination node.

[3] URL: http://www.isi.edu/nsnam/ns/, version 2.33.

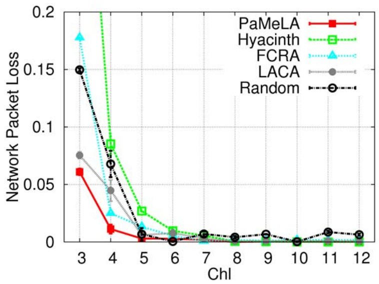

Figure 7. Network-wide packet loss vs. *Chl*.

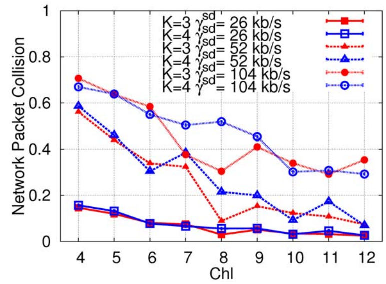

Figure 8. Network-wide collision, probability with $K = 3$ and $K = 4$.

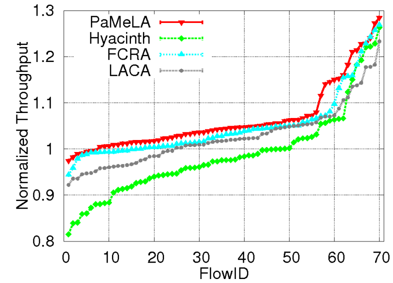

Figure 9. Normalized throughput per traffic flow,with $K = 3$, $Chl = 4$, γ^{sd}=26 Kb/s.

All metrics have been collected both per traffic flow and as network aggregates. Per traffic flow results are sorted in increasing values to improve readability.

C. Simulation results

The channel assignment and routing output with all the combinations of *K*, *Chl*, and the transmission rates have been tested through simulation. In the following we only report a sub-set of the results obtained for limited room availability.

We begin by showing in Fig. 7 the impact of increasing the number of non-overlapping radio channels available from the physical wireless network technology. Each node is equipped with 3 NICs and γ^{sd} is 26 Kb/s. The number of channels, 3 and 12, correspond to the number of non-overlapping channels available in IEEE 802.11b and 802.11a, respectively. The other numbers of channels correspond to the cases when some of the wireless channels might be already in use by the access network or some other networks. This experiment demonstrates that the channel assignment algorithm can adapt itself with the number of available channels. If a new channel becomes available, the algorithm can split the collision domain and thus increase the cross-section throughput.

Figure 8 shows that increase the number of NICs on each node does not help as much as increase the channels in the network. We can see that with 3 NICs the network performs worst that with 4 NICs per node, but this increase is not meaningful.

Figure 9 shows the normalized throughput in respect to the random channel assignment. We show the case with 3 radios, 4 channels and γ^{sd} equal to 26 Kb/s. Some studies [25] have been conducted to estimate the maximum throughput is arbitrary wireless networks with SINR but the results are still for a simplify SINR model.

Figure 10 and Figure 11 show the case with 3 radios and 8 channels and γ^{sd}, 26 Kb/s (a), 52 Kb/s (b) and 104 Kb/s (c). Figure 10 shows the packet loss occurred for each flow, the correspondent packet collision is shown in Fig. 11. These results show that the packet loss is decreased because the collisions are decreased.

V. Conclusions and Future Work

In this paper we have proposed a joint channel assignment and routing algorithm for multi-radio multi-channel WMNs, called PaMeLA, which consists of splitting the overall problem into a number of local ILP sub-problems.

We have shown that the execution time of PaMeLA is relatively low, which makes it feasible to be implemented in an operational WMN with non-specialized hardware, even for large WMNs with tens of nodes. The performance of PaMeLA is assessed through detailed packet-level simulation with a square-grid topology, with several combinations of the number of available channels and NICs per node. The results have shown that it improves significantly the network performance, in terms of the packet loss of all traffic flows, with respect to many state-of-the-art channel assignment and routing algorithms.

While the framework of PaMeLA is generic, some components are optimized for square-grid topology WMNs with a single gateway located in a corner. The extension of the specialized functions to the general case is an ongoing research activity. Furthermore, another research direction that can be followed is the design of a protocol to enable the online collection of network data, like channel conditions and traffic load, and to enforce the channel assignment and routing produced by PaMeLA.

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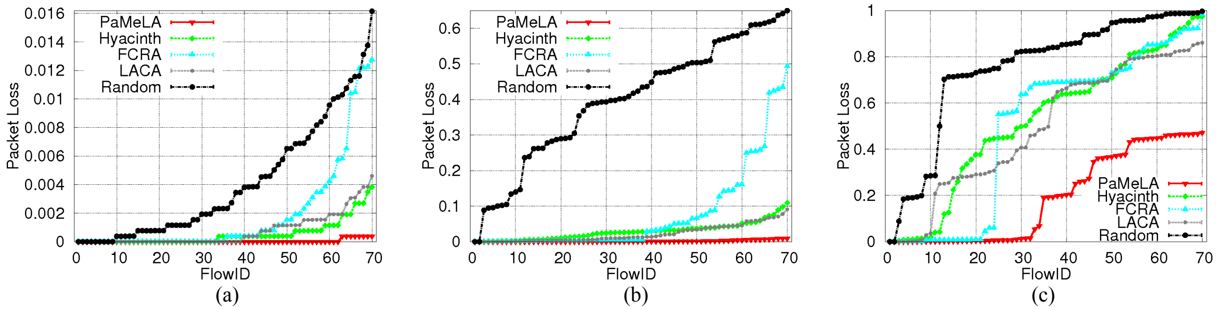

Figure 10. Packet loss per traffic flow, with $K = 3$, $Chl = 8$, and γ^{sd} equal to 26 Kb/s (a), 52 Kb/s (b), 104 Kb/s (c).

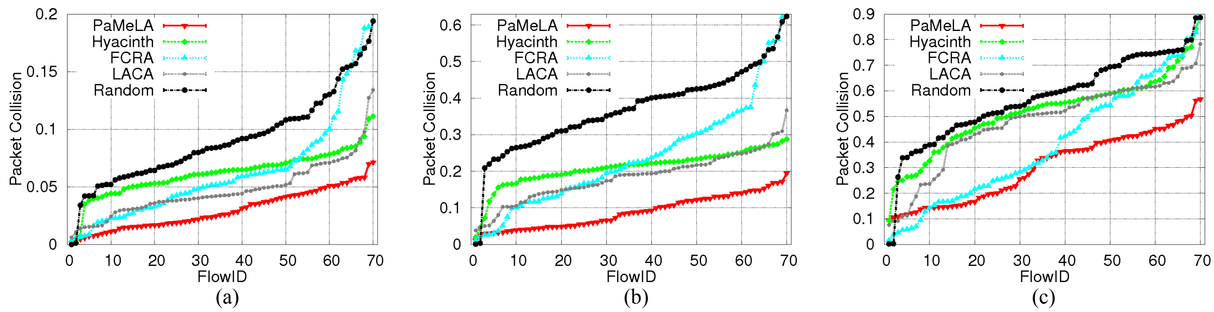

Figure 11. Collision probability per traffic flow, with K = 3, Chl = 8, and γ^{sd} equal to 26 Kb/s (a), 52 Kb/s (b), 104 Kb/s (c).

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