Towards Efficient Use of Radio Resources in Single Channel Wireless Mesh Networks

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Abstract— **In this paper, we address the radio resource utilization efficiency in single channel wireless mesh networks (WMNs) while considering the mobility of users and when multiple simultaneous connections on the same channel exist in the network. To achieve this, we use clustering. We first identify through analytical models and simulations the cases where clustering is helpful. Building on these results, we propose two clustering schemes that take into consideration the mobility properties of users in order to improve the WMN performance. We prove that both schemes can achieve significant gains in terms of radio resource utilization, especially when the number of simultaneous connections in the network increases. Specifically, we show that the first scheme fits better low-connected wireless mesh networks, whereas the second scheme is more suitable for highly-connected networks.**

Index Terms— **Wireless mesh networks, mobility management, clustering, radio resources, performance analysis.**

I. INTRODUCTION

Wireless mesh networks (WMNs) have emerged recently as a promising solution to support the increasing demand for wireless access to the Internet. A variety of applications are expected to benefit from WMNs such as "community wireless networks" [1]. Typically, a WMN comprises static wireless mesh routers, also called access points (APs). Each AP serves multiple mobile users and connects them through multi-hop wireless routing to the wired network. The mesh nodes connected directly to the wired network are called gateways. They represent the traffic sinks and sources to the WMN.

In WMNs, two types of messages are exchanged between the gateway and a mobile user: data and signaling messages. Specifically, each time the mobile user moves to a new AP, it notifies the gateway with its new location. These signaling messages are relayed through multi-hop wireless links to the gateway. For convenience, we assume a multi-channel WMN where interfering wireless links operate on different channels, enabling multiple parallel transmissions. In order to achieve an efficient use of the radio resources in such multi-hop wireless networks, we need to minimize the average number of wireless links occupied by a mobile user during its service (i.e., while exchanging both data and signaling packets). Henceforth, we refer to this metric as the radio resource utilization (RRU) cost.

Reducing the RRU cost per user improves the utilization efficiency of the WMN resources and thus increases the number of accepted subscribers to the WMN service. This means more profits to the service provider from the existing infrastructure.

One way to achieve this is by means of clustering as demonstrated in our study. Accordingly, the WMN is divided into a set of virtual clusters, covering all the nodes in the network. In each cluster, a node would serve as a clusterhead (CH). It operates as an intermediate node between the gateway and the APs inside the cluster. The main idea behind WMN clustering is to restrict a major part of the exchanged signaling messages due to the mobility of users to a local area (i.e., the cluster). As such, less wireless links are used by the signaling messages, which reduces the RRU cost and improves thus the total network throughput.

Numerous proposals for clustering and hierarchical routing schemes have been proposed in the literature, especially in the context of ad-hoc networks. Clustering in such networks is introduced mainly to handle efficiently the frequent network topological changes due to ad-hoc nodes mobility [2] – [4]. Designed for ad-hoc networks, these protocols are not suitable for typical WMN applications for two main reasons: the static topologies of WMNs and the different communication patterns. Indeed, the communications in WMNs are performed chiefly between the gateways and their associated APs, and not directly between arbitrary pairs of mesh nodes.

Other works [5] [6] proposed d-hop clustering algorithms in wireless ad-hoc networks such that a node in any cluster is at most d hops away from the CH. However, the clusters have the same radius d, an additional constraint, which may lead to unsatisfactory results regarding the RRU cost minimization. Again, because of the unique characteristics of WMNs, existing ad-hoc clustering approaches can not be directly used.

In the context of WMNs, relevant works to clustering are [7] [8]. These works attempt to integrate the WMNs with the wired backbone by dividing the WMN into a minimum number of disjoint macro-clusters, where each macro-cluster is assigned to a gateway node that connects directly to the wired network. The objective is therefore to minimize the number of deployed expensive gateways (i.e., number of macro-clusters) required to connect all APs to the wired network subject to several QoS constraints. In our study, we focus rather on virtual clustering inside each macro-cluster. Our objective is to divide the macro-cluster into virtual micro-clusters in order to minimize the RRU cost in the WMN. Hence, while macro-clustering is performed to minimize the number of required gateways, micro-clustering is performed to optimize the RRU cost in WMNs. Both clustering approaches are complementary to achieve cost-effective WMNs.

To this end, we proposed in [9] two mobility-aware clustering algorithms in multi-channel WMNs. The first scheme, called Optimal Static Clustering (OSC), assumes that the clusters are static and disjoint. In this case, we determine the optimal cluster placement that minimizes the RRU cost by formulating the placement problem as an integer linear program (ILP). In the second scheme, called Distributed Clustering Algorithm for Mesh networks (DCAM), the clusters may overlap. In this case, the cluster placement is done in a distributed manner. In essence, the DCAM approach is proposed to alleviate the time complexity entailed by the OSC approach due to the time consuming resolution of the associated ILP problem.

In this paper, we investigate the performance of our proposed clustering algorithms in terms of RRU cost in single-shared channel WMNs. Specifically, as opposed to [9], we study the case of a WMN with multiple simultaneous connections on the same channel, which is more likely to be the case in real networks. In this context, the cases of OSC, classical WMNs (i.e., without clustering, denoted by WC) and the well-known distributed clustering algorithm (DCA) [4], which is proposed originally for ad-hoc networks, are used for comparison with DCAM, since no clustering approach for mobility management in WMNs has been previously proposed in the literature. Note that in both OSC and DCAM clustering schemes, we take into account the mobility properties of the users.

To gauge the effectiveness of our proposals, we also develop a Markov chain-based model to analyze the DCAM algorithm. In the OSC case, the problem is formulated as an ILP. Building on these models, we derive the expressions of RRU cost, data delivery cost and registration updates cost for both cluster-based and classical WMNs. We evaluate the performance of our algorithms using random meshed topologies under various mobility and traffic scenarios and using ETX [10] (Expected Transmission Count) as routing metric.

The remainder of this paper is organized as follows. Section II presents a description of the network model and the problem statement. Section III introduces the OSC method and describes the associated ILP formulation. Section IV presents the DCAM algorithm and its analytical model. In section V, some numerical and simulation results are provided. Finally, section VI concludes this paper.

II. MODEL AND PROBLEM DESCRIPTION

A. Network Model

We represent a WMN by an undirected graph $G(V, E)$, called a connectivity graph. Each node $v \in V$ represents an AP with a circular transmission range R_t. The neighborhood of v, denoted by $N_e(v)$, is the set of nodes residing in its transmission range. A bidirectional wireless link exists between v and every neighbor $u \in N_e(v)$ and is represented by an edge $(u, v) \in E$. The number of neighbors of a vertex v is called the connectivity degree of v, denoted by $\delta(v)$. The average connectivity degree $\overline{\delta}$ of a graph G is called the graph degree and defined by $\frac{1}{|V|}\sum_{v \in V}\delta(v)$. In our study, we represent the graph connectivity by a connectivity matrix. The connectivity matrix of $G(V, E)$ is a matrix with rows and columns labeled by the graph vertices V, with a 1 or 0 in position (m, n) according to whether v_m and v_n are directly connected or not. We associate to the connectivity matrix a distance matrix D to represent the distance between every pair of nodes in the graph G according to a specific routing metric.

B. Problem Description

In this paper, we approach the efficient mobility management of users in single-shared channel WMNs by minimizing the radio resource utilization (RRU) cost of a mobile user during its service. To achieve this, we use clustering. Accordingly, we divide the WMN into a set of virtual clusters, covering all the nodes in the network.

For mobility management, we define two types of handoffs: Intra-cluster and Inter-cluster handoffs. An Intra-cluster handoff occurs when a user moves between two APs that belong to the same cluster. On the other hand, an Inter-cluster handoff occurs when a user moves between two APs belonging to different clusters. To maintain connectivity during user mobility, the gateway keeps a record of the current user cluster (i.e., CH's identity). Each time the user crosses a cluster boundary, it updates the system with its new location by sending a registration update message to the gateway through the CH of the new visited cluster. We call this kind of registration updates *GW registration*. In contrast, when an Intra-cluster handoff occurs, the update registration message will be sent only to the current CH and will not be forwarded to the gateway. This kind of registration is called *CH registration*.

With regard to data packets, an incoming packet from the backbone to the mobile user (i.e., downlink traffic) is first intercepted by the gateway. Then the packet is forwarded to the current user CH, which relays the data packet to the corresponding AP for delivery. In turn, data packets transmitted by the mobile user to the wired network (i.e., uplink traffic) are directly routed to the gateway, for instance, according to the shortest path, without requiring to pass through the CH.

The RRU cost of a mobile user involves two terms, i.e., the first one related to the resources used by the data packets and the second term is related to the resources used by the signaling messages necessary for managing user mobility. We refer to the first term as the *data delivery cost* and to the second term as the *registration updates cost*.

Clearly, an efficient clustering policy must minimize the sum of these two terms. It must achieve a balance regarding the cluster sizes. Indeed, a WMN with small-size clusters will result in an increasing number of expensive inter-cluster handoffs instead of low-cost intra-cluster handoffs during the user mobility. On the other hand, large-size clusters will reduce the number of expensive inter-cluster handoffs. However, this will result in an increase of the data delivery cost. In view of this, a tradeoff between these two requirements must be achieved by optimally constructing the clusters in order to minimize the RRU cost.

To address the above-mentioned tradeoff, we suggest two clustering schemes. The first assumes that the clusters are static and disjoint. The second considers a distributed algorithm to construct the virtual clusters, which are neither static nor disjoint and their placement depends on the user's mobility.

III. OPTIMAL STATIC CLUSTERING

In this section, we address the optimal placement of clusters in WMNs using the optimal static clustering (OSC) method. We formulate the clustering problem as follows. Given a WMN of N nodes, find the disjoint sets of APs (i.e., clusters) that minimizes the total RRU cost subject to the delay constraint. The delay constraint is translated into an upper bound D_{max} on the number of hops that a packet can cross between the gateway and the AP connecting the mobile user. In other words, the indirect path between the gateway and the mobile user's AP through the current CH must be less or equal to D_{max}.

ILP Formulation

Let $N = |V|$ be the number of APs. The APs are denoted by AP_i, $(i = 1, ..., N)$. We denote by $AP_1 \in V$ the gateway (GW) that connects the WMN to the wired network. We introduce a binary variable a_i to indicate whether an $AP_i \in V$ is set up as a CH or not. To represent CHs allocation for APs, we define another binary variable $b_{i,j}$ which takes the value of 1 whenever AP_j, $j = 1, ..., N$, is assigned to the CH AP_i, $i = 1, ..., N$. M is an upper bound on the number of clusters that can be formed. m_{sig} and m_{data} represent the average size of signaling messages used for registration updates and data packets, respectively. $1/\mu$ represents the mean sojourn time of a mobile user in a subnet (i.e., AP), and λ is the downlink packet transmission rate (in terms of packets/s). For each user inside the WMN, let also its mobility pattern be defined by the process $\{Y(t), t \geq 0\}$, where $Y(t) = AP_i$ represents the user's location at time t. Given the matrix of distances D between APs, the steady probability Π_i that the mobile user is located at the physical subnet AP_i, and the transition probability matrix P of the process Y, our objective function will be to minimize the RRU cost in the WMN, expressed as follows:

$$\mathit{RRU\_Cost} = \alpha \times \mathit{Reg\_Update\_Cost} + \beta \times \mathit{Data\_Delivery\_Cost} \quad (1)$$

where $\alpha = \frac{2\ \mu\ m_{sig}}{2\mu\ m_{sig} + \lambda\ m_{data}}$ and $\beta = \frac{\lambda\ m_{data}}{2\mu\ m_{sig} + \lambda\ m_{data}}$ are the proportion of the amount of signaling messages and the proportion of data packets among the total traffic generated by a mobile user, respectively. The $\mathit{Reg\_Update\_Cost}$ can be written as follows:

$$\mathit{Reg\_Update\_Cost} = \sum_{i=1}^{N} \Pi_i \times \mathit{Update\_Cost}(i) \quad (2)$$

where $\mathit{Update\_Cost}(i)$ is the cost of the registration updates when the mobile user leaves the AP_i. It is given by:

$$\mathit{Update\_Cost}(i) = \sum_{j=1}^{N} \Big(P(i,j) \times \sum_{k=1}^{N} b_{k,j} \times \Big[d(k,j) + (b_{k,j} - b_{k,i})\ d(k,GW) \Big] \Big) \quad (3)$$

where $d(i,j) = d(AP_i, AP_j)$ is the path length between AP_i and AP_j according to a specific routing metric, and $P(i,j) = P(AP_i, AP_j)$ denotes the transition probability from AP_i to AP_j. Likewise, the $\mathit{Data\_Delivery\_Cost}$ can be expressed as:

$$\mathit{Data\_Delivery\_Cost} = \sum_{i=1}^{N} \Pi_i \times \mathit{Delivery\_Cost}(i) \quad (4)$$

where $\mathit{Delivery\_Cost}(i)$ is the data delivery cost of downlink traffic when the mobile user is connected to AP_i:

$$\mathit{Delivery\_Cost}(i) = \sum_{j=1}^{N} b_{j,i} \times \big[d(i,j) + d(j,GW) \big] \quad (5)$$

Hence, our ILP problem can be formulated as follows with the objective function:

$$\min \Big\{ \mathit{RRU\_Cost} \Big\}$$

subject to:
(a) $\forall j = 1, ..., N : \sum_{i=1}^{N} b_{i,j} = 1$
(b) $\forall i, j = 1, ..., N : a_i \geq b_{i,j}$
(c) $a_1 = a_{GW} = 1$
(d) $\forall i = 1, ..., N : a_i = b_{i,i}$
(e) $\sum_{i=1}^{N} a_i \leq M$
(f) $\forall j = 1, ..., N : \sum_{i=1}^{N} b_{i,j} \times \Big(d(j,i) + d(i,GW) \Big) \leq D_{max}$
(g) $\forall i = 1, ..., N : a_i \in \{0, 1\}$
(h) $\forall i, j = 1, ..., N : b_{i,j} \in \{0, 1\}$

Condition (a) denotes that each AP is assigned to one and only one CH. Inequality (b) implies that a CH has to be set up before being assigned APs. Inequalities (c) and (d) ensure that the gateway can not be assigned to another cluster and each CH belongs to the cluster that it manages. Inequality (e) provides an upper bound on the number of the constructed clusters that can be parameterized by the WMN administrator. For instance, assigning to M the value of 1, implies a WMN without clustering. On the other hand putting $M = N$, implies that all the APs have the capability to operate as CHs. Inequality (f) traduces the delay constraint. The last two conditions indicate that a_i and $b_{i,j}$ are binary variables.

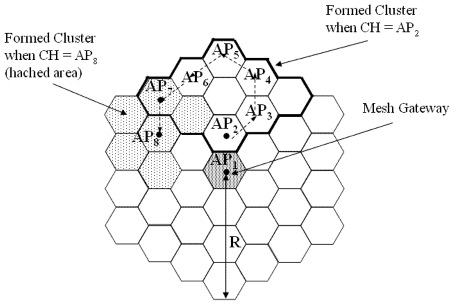


Fig. 1. The DCAM clustering scheme: illustration of the clusters associated to CHs AP_2 and AP_8.

We will show in section IV-B, how to derive the vector Π and the transition probability matrix P, which are used as inputs in our ILP formulation.

IV. DISTRIBUTED CLUSTERING ALGORITHM

In this section, we propose a distributed clustering approach, which is a new alternative to divide the WMN into clusters while avoiding the time complexity of the static approach based on the time consuming ILP problem resolution (see section V).

A. The DCAM algorithm

Like OSC, the DCAM algorithm divides the WMN into virtual clusters where the mobile user limits its registration updates within its local area, instead of communicating to the far away gateway. As a distinguishing key feature, the DCAM clusters are constructed in a distributed manner and may overlap as opposed to the disjoint and centrally calculated OSC clusters. Moreover, the virtual cluster construction with DCAM depends on the mobile user trajectory. It depends on the relative position of the old and the new APs with respect to the gateway and on the delay constraint.

To understand the functionalities of DCAM, let us consider the simple example presented in Fig. 1, where an hexagon-based regular wireless mesh topology is used. The gateway is placed at the center of the WMN. We assume that $D_{max} = 4$.

Assume that the user activates his mobile terminal at AP_2. Instantaneously, the mobile terminal registers to the gateway through the AP_2, which becomes the mobile user CH. The associated cluster to the current CH (i.e., AP_2) is composed of nine APs as shown in Fig. 1. These APs satisfy both conditions regarding the delay and registration cost. Indeed, as long as the mobile user remains in this cluster, the length of its indirect path to the gateway through the CH AP_2 is equal or less than D_{max} (i.e., it fulfills the delay constraint). In addition, a *CH registration* cost (in terms of occupied wireless links by the signaling messages) is cheaper than a *GW registration*. In this case, the mobile user carries out a local registration with the CH AP_2. Once it leaves this cluster, it performs a *GW registration* and the new serving AP becomes the new CH of the new cluster.

The condition on the registration updates cost is no longer verified when the user enters subnet AP_8. Hence, it registers directly to the gateway and the new visited AP_8 becomes the new CH of the new cluster. In this case, the new cluster managed by AP_8 is composed of six APs as shown in Fig. 1.

We can see that AP_7 belongs to both clusters managed by CHs AP_8 and AP_2. Indeed with DCAM, the mobile user can be attached to different CHs when visiting AP_7. According to the mobile user trajectory, i.e., the tuple (old AP, old CH), the new visited AP assigns the new CH to the user. In our example, when the mobile user moves to AP_7 with the tuple (AP_6, AP_2) it registers to the CH AP_2. The new state of the mobile user becomes (AP_7, AP_2). On the other hand, when the mobile user visits AP_7 while having (AP_8, AP_8) as the current state, it registers to the CH AP_8. The new mobile user state is therefore (AP_7, AP_8). This simple example shows clearly the dynamic and distributed properties of the DCAM algorithm.

B. Analytical Model

In this section, we introduce a mathematical model based on Markov chains to evaluate the performance of the DCAM method in terms of RRU cost, data delivery cost and registration updates. The elaborated model will be also used to derive some performance metrics that are required as inputs in the ILP formulation of the OSC method.

Assume a random meshed wireless network composed of N APs denoted by AP_i $(i = 1, .., N)$ where AP_1 is the gateway. In our study, we consider a general two-dimensional (2-D) random walk mobility model [11]. Accordingly, a mobile user connected to AP_i moves to one of the neighboring subnets with equal probability p (i.e., $p = \frac{1}{\delta(AP_i)}$, where $\delta(AP_i)$ is the AP_i connectivity degree). Using these probabilities, we construct the transition probability matrix $P = [p_{ij}]$ between pairs of mesh nodes. This matrix is used as an input parameter to solve the ILP problem described in section III.

Let $X(t)$ be the user's state within the WMN at time t defined by the tuple (AP_i, AP_j), where AP_i is the current AP and AP_j is the current user's CH. The sojourn time of a mobile user in a subnet AP_i is assumed to be exponentially distributed with the mean $1/\mu$. The process $\{X(t), t \geq 0\}$ is therefore Markovian with continuous time and finite state space $\mathcal{S} = \{(AP_i, AP_j) | 1 \leq i \leq N, AP_j \in E_{AP_i}\}$, where E_{AP_i} is the set of possible CHs that a mobile user can register to when it is connected to AP_i. In other words, $AP_j \in E_{AP_i}$ if and only if AP_i belongs to the cluster managed by AP_j, i.e., it satisfies the following relation:

$$AP_j \in E_{AP_i} \text{ if and only if } \begin{cases} d(AP_i, AP_j) < d(AP_i, GW) \\ \& \\ d(AP_i, AP_j) + d(AP_j, GW) \leq D_{max} \end{cases} \tag{6}$$

Recall that $d(x, y)$ denotes the path length (in terms of number of hops) between x and y according to a specific routing metric. Note that the first condition in (6) ensures a *CH registration* cost is less than a *GW registration*. The second condition ensures that the mobile user fulfills the delay constraint.

In the following, we calculate the discrete-time transition probability matrix Q derived from the Markov chain $X(t)$ when leaving a generic state (AP_i, AP_j). Let $AP_{i'}$ denote the next visited AP by the mobile user (i.e., $AP_{i'} \in N_e(AP_i)$). Hence, the mobile user moves to subnet $AP_{i'}$ with a probability $p = 1/\delta(AP_i)$. According to whether $AP_{i'}$ belongs or not to the current cluster managed by the CH AP_j, we can identify the next user's state.

Specifically, if this is the case (i.e., $AP_j \in E_{AP_{i'}}$), the mobile user will transit to the state $(AP_{i'}, AP_j)$. In this case, the mobile user performs a local registration to the current CH AP_j. Henceforth, we denote by $\mathcal{A}$ the event that $AP_j \in E_{AP_{i'}}$ (see (6)). On the other hand, if $\mathcal{A}$ is not satisfied, the mobile user registers to the gateway and the new AP becomes the CH of the new cluster. As such, the mobile user transits to state $(AP_{i'}, AP_{i'})$. Consequently, we have:

$$\begin{cases} Q\Big((AP_i, AP_j), (AP_{i'}, AP_j)\Big) = p \cdot 1_{\mathcal{A}} \\ Q\Big((AP_i, AP_j), (AP_{i'}, AP_{i'})\Big) = p \cdot 1_{\bar{\mathcal{A}}} \end{cases}$$

where $1_{\mathcal{A}}$ (respectively $1_{\bar{\mathcal{A}}}$) is the indicator function of the condition $\mathcal{A}$ (respectively $\bar{\mathcal{A}}$), i.e., it is equal to 1 if the condition $\mathcal{A}$ (respectively $\bar{\mathcal{A}}$) is true and 0 otherwise.

Based on the above analysis, we derive the transition probability matrix Q. Then, the steady state probability vector $\pi = [\pi_s]$ is obtained by resolving the following system:

$$\pi Q = \pi \text{ and } \sum_{s \in \mathcal{S}} \pi_s = 1 \tag{7}$$

It is worth noting that using the vector π, we can derive the steady probability $\Pi = [\Pi_i]$ that the mobile user is connected to the AP_i $(i = 1, ..., N)$. This vector Π, is used as an input parameter in the ILP formulation of the OSC approach. This vector can be derived as follows, using the steady state probabilities $\pi_s = \pi(AP_i, AP_j)$ of the states $s = (AP_i, AP_j)$:

$$\Pi_i = \Pi(AP_i) = \sum_{AP_j \in E_{AP_i}} \pi(AP_i, AP_j) \tag{8}$$

Building on these results, we evaluate hereafter the performance of the DCAM and OSC methods in terms of RRU cost. To do so, we calculate the data delivery and signaling costs.

1) Data Delivery Cost: It is the average number of wireless links used for packet delivery between the gateway and the current serving AP (i.e., in the downlink direction). In DCAM, the data delivery cost metric can be written as follows:

$$Data\_Delivery\_Cost(\text{DCAM}) = \sum_{s \in \mathcal{S}} \pi_s \times \Big(d(\mathit{AP(s)}, \mathit{CH(s)}) + d(\mathit{CH(s)}, \mathit{GW})\Big) \tag{9}$$

where $s = (\mathit{AP(s)}, \mathit{CH(s)})$.

For the OSC method, the data delivery cost can be simply given by substituting (5) in (4).

In the case where clustering is not considered, packets are delivered directly to the mobile user without passing through the CH. Hence, the data delivery cost is given by:

$$Data\_Delivery\_Cost(\text{WC}) = \sum_{i=1}^{N} \Pi_i \times d(i, GW) \tag{10}$$

2) Registration Updates Cost: It is representative of the average number of occupied wireless links by the signaling messages exchanged in the WMN when the mobile user moves to a new AP. In both DCAM and OSC methods, a *CH registration* is required as long as the mobile user remains in the same cluster. Otherwise, a *GW registration* is performed.

Considering the DCAM method, the average registration updates cost when leaving the state $s = (AP(s), CH(s))$ to a state $s' = (AP(s'), CH(s'))$ can be written as follows, using the transition probability matrix Q:

$$Update\_Cost(s) = \sum_{s' \in \mathcal{S}} Q(s, s') \times \mathcal{C}(s, s') \tag{11}$$

$$\text{where} \quad \mathcal{C}(s, s') = \begin{cases} d\big(\mathit{AP(s')}, \mathit{CH(s')}\big) & \text{if } \mathit{CH(s')} = \mathit{CH(s)} \\ d\big(\mathit{AP(s')}, \mathit{GW}\big) & \text{if } \mathit{CH(s')} \neq \mathit{CH(s)} \end{cases}$$

The total registration updates cost can be thus written as:

$$Reg\_Update\_Cost(\text{DCAM}) = \textstyle\sum_{s \in \mathcal{S}} \pi_s \times Update\_Cost(s) \tag{12}$$

Considering the OSC method, the registration updates cost can be expressed by replacing (3) in (2).

When the clustering policy is not considered, the registration updates cost is given by:

$$Reg\_Update\_Cost(\text{WC}) = \sum_{i=1}^{N} \Pi_i \times Update\_Cost(i) \tag{13}$$

where $Update\_Cost(i)$ is the cost of registration updates when the mobile user moves to the AP_i, which is simply equal to $d(AP_i, GW)$. Hence, the registration updates cost shown in (13) is equal to the data delivery cost shown in (10). This is simply because both packet delivery and registration updates are always performed with the same node, which is the gateway.

3) RRU Cost: It is the radio resource utilization of a WMN where the profile of its mobile users are characterized by the pair (λ, μ). λ measures the average rate of traffic exchanged by each mobile user and μ describes the user mobility in the WMN. The expression of the RRU_Cost for the DCAM, OSC and WC cases can be simply obtained by replacing (9) and (12) in (1), (2) and (4) in (1), and (10) and (13) in (1), respectively.

V. NUMERICAL & SIMULATION RESULTS

In this section, we evaluate the efficiency of the proposed clustering algorithms (i.e., OSC and DCAM) in terms of RRU cost. Specifically, we study the gain they introduce compared to the DCA algorithm [4] as well as to the case where clustering is not used (i.e., the WC case), under various mobility and traffic scenarios and using the ETX [10] routing metric. Indeed, in single-shared channel environments, it has been demonstrated that the shortest path routing does not perform well since it does not account for the quality of radio links [10]. The analysis is achieved under the ns-2 simulator and using random meshed topologies. We considered different network sizes: 20, 60 and 100 APs, which are representative of small, medium and large single-gateway WMNs. However, due to the lack of space, we present only the results regarding to a 60-node random WMN. The maximum tolerable delay D_{max} inside the network is set equal to the maximal distance between the gateway and any AP. In addition, we considered different values of graph degree $\bar{\delta}$ and different number of simultaneous connections (i.e., number of active mobile users) in the network.

We recall that in our study, we use a random walk mobility model [11]. The sojourn time $1/\mu$ within an AP subnet is set equal to 10, 100 or 1000 seconds to represent very fast, fast or slow mobile users, respectively. In addition, we used different values of λ to represent different mobile user loads (i.e., light, moderate and heavy-traffic mobile user loads). Specifically, the values of λ and the associated quantity of downloaded traffic per user and per day are reported in Table I. To get an estimate from λ of the downloaded traffic per user, we assume that the average packet size is equal to 460 bytes (see [12]).

First, we will draw an in depth comparison between the OSC and DCAM clustering strategies based on their time complexities. To get an insight into the computation times needed by both methods to identify the set of clusters, let us consider Table II. The measurements are performed on a PC with 3.2 Ghz of CPU and 2.00 GB of RAM for a random WMN with N nodes varying between 7 and 91. The reported results show that the DCAM algorithm achieves great time saving compared to the OSC approach notably when N is high. Indeed, the time needed to resolve the OSC optimization clustering problem increases dramatically with the network size N since the number of variables and equations in the ILP formulation increases exponentially with N. In contrast, with DCAM, the clusters are set up automatically and in a distributed manner according to both conditions regarding the delay constraint and the registration updates cost (see (6)). In DCAM, each AP needs only to be aware of the distance table D to identify its virtual cluster when it operates as a CH. In view of this, the changes in the physical topology are more efficiently handled by DCAM, since it reacts much more quickly than OSC.

TABLE I
QUANTITY OF DOWNLOADED TRAFFIC PER USER PER DAY

λ (packets/s)	0.001	0.01	0.1	0.5	1	2	10
Traffic (Mbits/day)	0.318	3.18	31.8	159	318	636	3180

TABLE II
COMPUTATION TIMES OF OSC AND DCAM METHODS

N	7	19	37	61	91
OSC Time (seconds)	0.047	0.187	33.218	674.078	6570.77
DCAM Time (seconds)	0.31	0.98	1.97	7.81	26.05

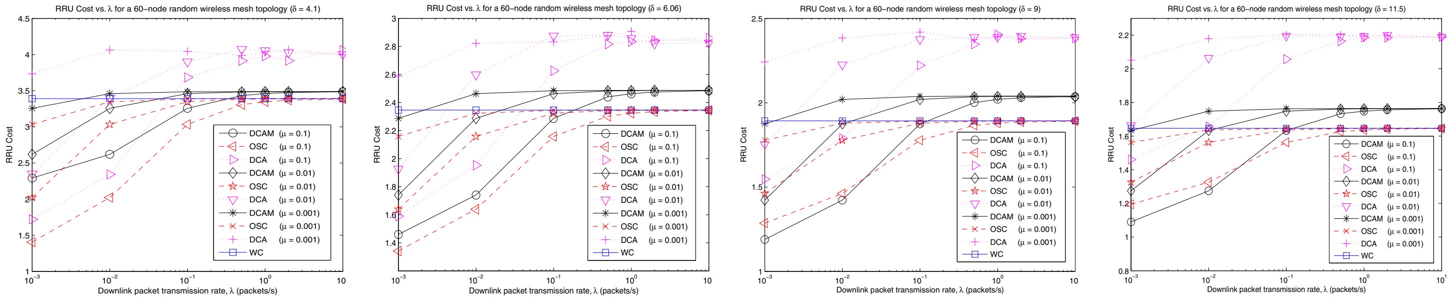
Let us now focus on the comparison among the different strategies (OSC, DCAM, DCA and WC) in terms of RRU cost. The results are reported in Figs. 2 and 3.

Recall that the RRU cost is a weighted sum of the data delivery and registration updates costs. In the WC case , the RRU cost equals the data delivery and the registration updates cost. It is simply the average length of the ETX-based routing path between each AP_i ($i = 1, ..., N$) and the gateway weighted by the probability Π_i that the mobile user is connected to AP_i during its movement. Hence, when interferences in the WMN are negligible (i.e., case of only one active connection at a time), the RRU cost with the WC approach is insensitive to the mobile user profiles (i.e., λ and μ), and is a constant metric that depends only of the physical topology (i.e., graph connectivity properties), as shown in Fig. 2. However, when interferences exist (i.e., case of multiple simultaneous connections in the network), the RRU cost of the WC approach is no longer constant and depends on the traffic and user mobility properties, as shown in Fig.3.

From these figures, we can also notice that the OSC approach achieves always better results than the WC case. We point out that the WC strategy can be seen as a particular case of the OSC one where the number of clusters is set equal to 1 and where the gateway is the only CH. In this regard, both strategies exhibit similar results when λ and $1/\mu$ have relatively large values. This is shown clearly in Figs. 2 and 3 by the asymptotic behavior of the OSC curves with respect to the WC ones. Obviously, in this range of λ and μ, the WC technique is preferred thanks to its simplicity compared to the OSC method even if they provide similar results.

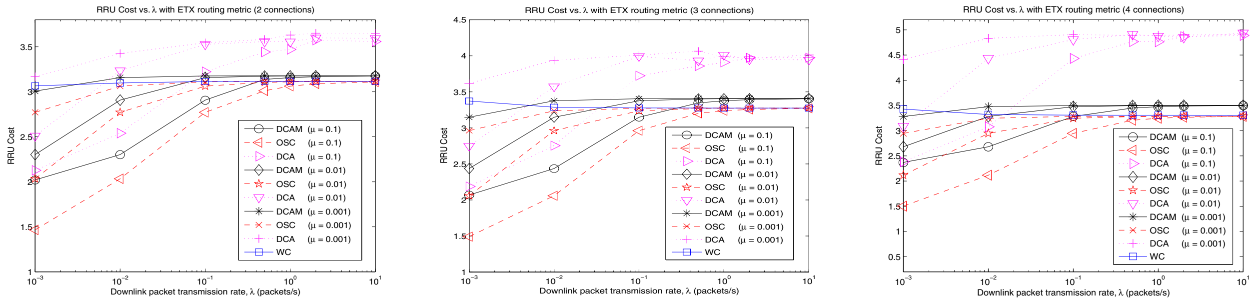
On the other hand, for small and moderate values of λ and $1/\mu$, we can observe that minimal RRU cost is always obtained either by our OSC or DCAM schemes according to the network graph properties (i.e., average node degree $\bar{\delta}$). Our proposed clustering protocols outperform indeed the DCA scheme, which is proposed originally for ad-hoc networks. Specifically, Fig. 2 shows that for small values of $\bar{\delta}$ (i.e., $\bar{\delta} = 4.1$ and $\bar{\delta} = 6.06$), the OSC approach provides the best results and when $\bar{\delta}$ gets moderate to high values (i.e., $\bar{\delta} = 9$ and $\bar{\delta} = 11.5$), the DCAM approach is the best solution. Indeed, using the DCAM approach, the cluster size in terms of number of APs around each CH increases with the graph degree $\bar{\delta}$ since more and more APs satisfy the delay and the registration updates cost constraints shown in (6). Hence, the registration updates cost decreases considerably with $\bar{\delta}$ for the DCAM case. However, the decrease of this cost with $\bar{\delta}$ is less significant in the OSC case, since the OSC approach tries to minimize the registration updates cost without deteriorating the data delivery cost. Thus, DCAM provides a lower RRU cost for this range of $\bar{\delta}$. In this regards, the DCAM approach does not limit its gain over OSC to the reduction of the computation time, but it can also achieve further gain regarding the RRU cost.

Fig. 4 shows the impact of the number of simultaneous connections N_c in the network on the RRU cost. We can



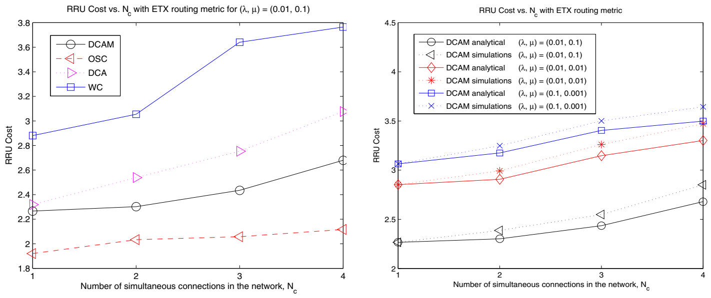
(a) $\bar{\delta} = 4.1$ (b) $\bar{\delta} = 6.06$ (c) $\bar{\delta} = 9$ (d) $\bar{\delta} = 11.5$

Fig. 2. RRU cost in a 60-node random WMN with 1 active connection at a time



(a) 2 simultaneous connections (b) 3 simultaneous connections (c) 4 simultaneous connections

Fig. 3. RRU cost in a 60-node random WMN with simultaneous active connections



(a) (b)

Fig. 4. Impact of the number of simultaneous connections in the network on radio resource utilization

notice that our clustering schemes still achieve significant gain compared to the WC and DCA cases, especially for high values of N_c. Moreover, Fig. 4(a) shows that the RRU cost increases with the increase of N_c for all schemes. Indeed, increasing the number of simultaneous connections N_c increases interferences and collisions inside the WMN. As such, each bit needs to be transmitted more times to be correctly received by the destination and thus occupies more resources.

Finally, Fig. 4(b) shows a comparison between the simulation and the analytical results for DCAM. Again, we can see that the analytical model is highly accurate when interferences in the WMN are negligible (i.e., case of only one active connection). However, the analytical model looses slightly and progressively its accuracy with the increase in the number of simultaneous connections. This deviation is expected since retransmissions due to collisions, which increase with N_c, are not captured by the analytical model.

VI. CONCLUSION

In this paper, we investigated the radio resource utilization efficiency in single channel wireless mesh networks (WMNs) with multiple simultaneous connections. We proposed two clustering schemes to improve the resource utilization in such networks. Based on both analytical models and simulations, we showed that the distributed clustering algorithm (DCAM) stands out as the best solution for highly-connected WMNs, whereas the optimal static clustering (OSC) scheme is the best solution for low-connected networks. In addition, we showed that our clustering techniques achieve significant gain compared to the well-known DCA algorithm, especially when the number of simultaneous connections in the network increases, which is more likely to be the case in real networks.

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